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ENERGY EFFICIENT ENGINE
SECTOR COMBUSTOR RIG TEST PROGRAM
TECHNOLOGY REPORT

by

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UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group
Commercial Products Division

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16. ABSTRACT
Under the NASA-sponsored Energy Efficient Engine program, Pratt & Whitney Aircraft has successfully completed a comprehensive combustor rig test using a 90-degree sector of an advanced two-stage combustor with a segmented liner.

Initial testing utilized a combustor with a conventional louvered liner and demonstrated that the Energy Efficient Engine two-stage combustor configuration is a viable system for controlling exhaust emissions, with the capability to meet all aerothermal performance goals. Goals for both carbon monoxide and unburned hydrocarbons were surpassed and the goal for oxides of nitrogen was closely approached.

In another series of tests, and advanced segmented liner configuration with a unique counter-parallel FINWALL® cooling system was evaluated at engine sea level takeoff pressure and temperature levels. These tests verified the structural integrity of this liner design.

Overall, the results from the program have provided a high level of confidence to proceed with the scheduled Combustor Component Rig Test Program.

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FOREWORD

The Energy Efficient Engine Component Development and Integration Program is being conducted under parallel National Aeronautics and Space Administration (NASA) contracts with Pratt & Whitney Aircraft Group and General Electric Company. The overall project is under the current direction of Mr. Carl C. Ciepluch, with Mr. John W. Schaefer serving as NASA's Assistant Project Manager for the Pratt & Whitney Aircraft effort under contract NAS3-20646. Mr. Daniel E. Sokolowski is the NASA Project Engineer responsible for the portion of the project described in this report. Mr. William B. Gardner is the manager of the Energy Efficient Engine program at Pratt & Whitney Aircraft Group, with Messrs. D. J. Dubiel, W. Greene, C. V. Sundt, S. Tanrikut and M. H. Zeisser, the engineers responsible for work described in this report.

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SECTION 1.0
SUMMARY

Under the NASA-sponsored Energy Efficient Engine Program, Pratt & Whitney Aircraft has completed a comprehensive test program using a 90-degree sector combustor rig that features an advanced two-stage combustor with segmented liners. This test program demonstrated that, with the exception of oxides of nitrogen, the combustor is capable of achieving all performance, structural and emissions goals for the Energy Efficient Engine Program. Furthermore, it has provided a high level of confidence to proceed with the scheduled Combustor Component Rig Test Program.

The Sector Combustor Rig Test Program was structured in three phases. The first phase consisted of a series of cold flow characterization, visualization and model tests to optimize the design of the fuel injectors. On the basis of these results, revisions were made to the carburetor tube injector to improve spray and jet penetration properties. Flow characterization test results were also used in the evaluation of the pilot zone fuel injector.

In the second phase, fourteen performance/emissions tests and two altitude relight tests were completed. These evaluations were performed using a sector combustor rig with conventional sheet metal louvered liners because of the flexibility to incorporate design changes. Testing demonstrated that the two-stage combustor is a viable approach for controlling exhaust emissions, with the capability to meet all aerothermal performance goals. Goals for both carbon monoxide and unburned hydrocarbon emissions were surpassed, while the goal for oxides of nitrogen was approached. Intentional perturbations to the combustor inlet profile showed no effect on performance or emissions. Also, combustion stability and altitude relight capability were verified.

The third phase of the program focused on evaluating the performance of the advanced segmented liner design with a unique counter-parallel FINWALL® cooling technique at engine sea level takeoff pressure and temperatures. A series of four tests verified the structural integrity of the liner design and showed that the segmented liner produced no adverse effects on overall system performance or exhaust emissions. However, injector-induced streak temperatures obtained by temperature sensitive paint analysis exceeded the predicted values. This condition will be addressed during the subsequent Combustor Component Rig Program. Post-test inspections indicated that the liners were in excellent condition, with no indications of cracking or buckling.

During the test program, approximately 500 hours of sector combustor rig testing were accumulated. Also, approximately 1000 performance/emissions data points were acquired. Table 1-I presents a synopsis of the test results.

TABLE 1-I
SUMMARY OF TEST RESULTS

	Goal	Louvered (2) Liner		Segmented (3) Liner	
Exhaust Emissions (max)					
Hydrocarbons(1)	0.4	0.18*	0.26**	0.26*	0.38**
Carbon Monoxide(1)	3.0	1.54*	2.07**	1.71*	2.30**
Oxides of Nitrogen(1)	3.0	3.80*	4.65**	3.85*	4.70**
Smoke, SAE Number	20	<1		4	
Pattern Factor	0.37 (Max)	0.15		0.26	
Section Pressure Loss, (%P_{T3})	5.5	5.37		5.22	
exit Radial Profile, °C (°F)	121 (250) (peak to avg)	21 (70)		65 (150)	

(*) As measured
(**) Includes margins for development and variability
(1) Environmental Protection Agency Parameter (pound pollutant/1000 pounds-thrust hour/cycle).
(2) Tested up to 1.6 MPa (230 psia).
(3) Tested up to 3.1 MPa (445 psia).

SECTION 2.0
INTRODUCTION

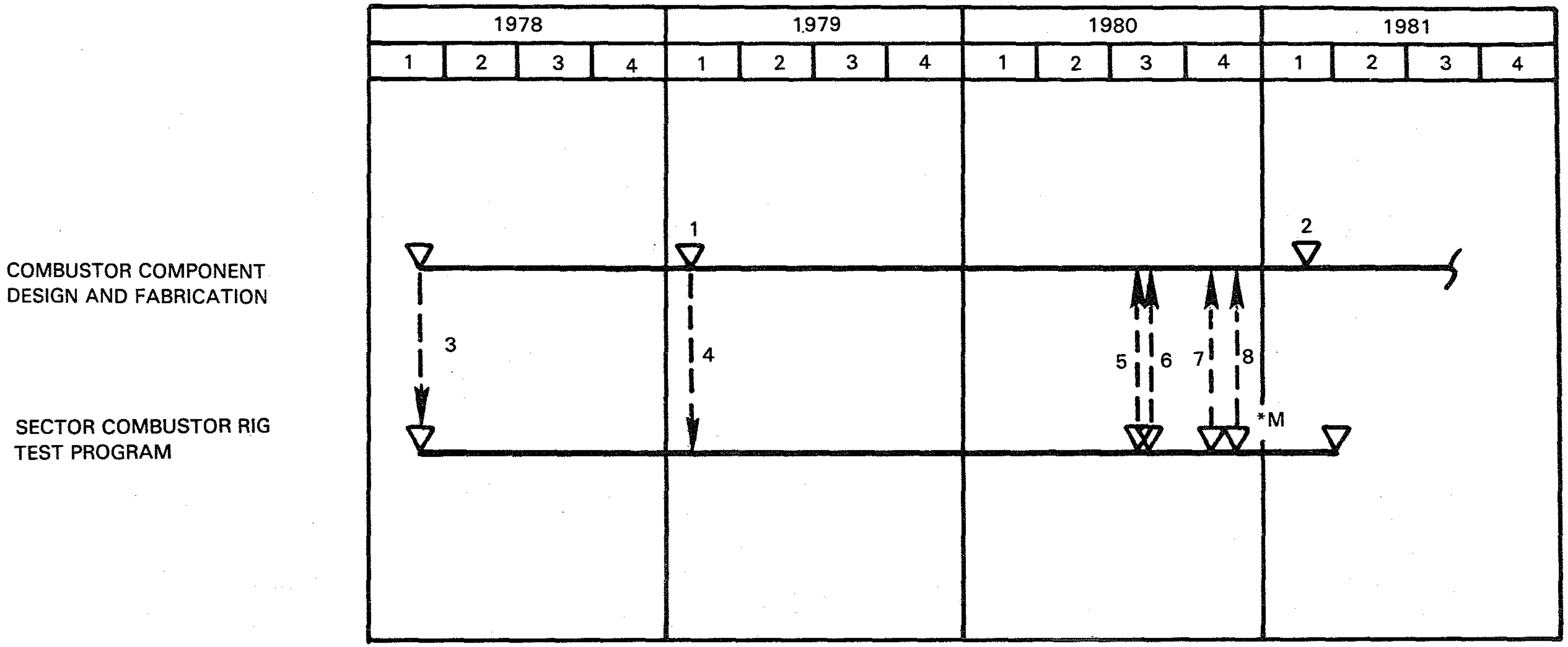
The Energy Efficient Engine Component Development and Integration Program, sponsored by the National Aeronautics and Space Administration, is directed towards developing the technology to achieve greater fuel efficiency for future commercial aircraft gas-turbine engines. The goals established for the overall program include a reduction in fuel consumption of at least 12 percent and a reduction in direct operating costs of at least 5 percent relative to the Pratt & Whitney Aircraft JT9D-7A base engine. To demonstrate the technology to attain these goals, the Energy Efficient Engine Program is organized into three tasks which involve the following:

Task 1	Propulsion System Analysis, Design and Integration
Task 2	Component Analysis Design and Development
Task 4	Integrated Core/Low Spool Design, Fabrication and Test

Under Task 2, an advanced combustion system is being developed for the Energy Efficient Engine. The component design incorporates numerous advanced technology features to provide a compact system that can substantially reduce emissions, reduce exit temperature pattern factor and increase durability. These features as well as the defined program goals will be demonstrated through a series of sector and full annular combustor rig tests, culminating with a comprehensive test in the integrated core/low spool test vehicle. With only minor exceptions, the combustor design is the same for both the flight propulsion system, which is the analytical study engine in the Energy Efficient Engine Program, and the integrated core/low spool test vehicle.

This report presents the results of the Sector Combustor Rig Test Program -- one of two supporting technology programs in the overall Energy Efficient Engine combustor component effort. This program was conducted to ensure timely interaction with the combustor component effort, as indicated in Figure 2-1. The following section, Section 3, presents a description of the sector rig, including the design goals and an overview of aerothermal and mechanical design of the Energy Efficient Engine combustor component. Section 4 describes the test program, test facilities and instrumentation. In Section 5, a complete discussion of the test results is presented. Concluding remarks pertaining to the test are in Section 6.

Three appendixes are included in this report. Appendix A provides a description of performance and emissions parameters. Appendix B contains a description of the test configurations, and Appendix C contains a test data summary for each of the sector combustor rig tests.



1 — COMPONENT PRELIMINARY DESIGN COMPLETED

2 — COMPONENT DETAILED DESIGN COMPLETED

3 — COMPONENT FLOWPATH AND AERODYNAMICS SPECIFIED

4 — COMBUSTOR LINER CONFIGURATION CHANGED FROM CONVENTIONAL LOUVERED DESIGN TO ADVANCED SEGMENTED DESIGN TO ACHIEVE REQUIRED LIFE

5 — PILOT ZONE FUEL NOZZLE CONFIGURATION DEFINED

6 — CARBURETOR TUBE CONFIGURATION SELECTED

7 — COMPONENT BULKHEAD/HOOD CONFIGURATION VERIFIED

8 — ADVANCED SEGMENTED LINER CONCEPT VERIFIED (*M = PROGRAM-CRITICAL MILESTONE)

Figure 2-1 Energy Efficient Engine Sector Combustor Rig Test Program Major Milestones

SECTION 3.0
SECTOR COMBUSTOR RIG DESIGN

3.1 OVERVIEW

The combustor component defined for the Energy Efficient Engine and illustrated in Figure 3.1-1 combines advances in aerodynamics and structural mechanics to provide a compact system capable of low emissions and high performance. Among these advances are a short curved-wall, dump prediffuser and an advanced segmented liner, which offers improved cooling and durability. Emissions reduction features in this combustor have evolved from the technology demonstrated in the prior NASA-sponsored Experimental Clean Combustor Program. One prominent example is the use of a two-stage combustion system based on the Vorbix (vortex burning and mixing) principle, which exploits the benefits of swirling air to promote complete fuel/air mixing for low emissions. In addition, results from the recent Energy Efficient Engine Diffuser/Combustor Model Test Program were instrumental in establishing the aerodynamic viability of the diffuser section.

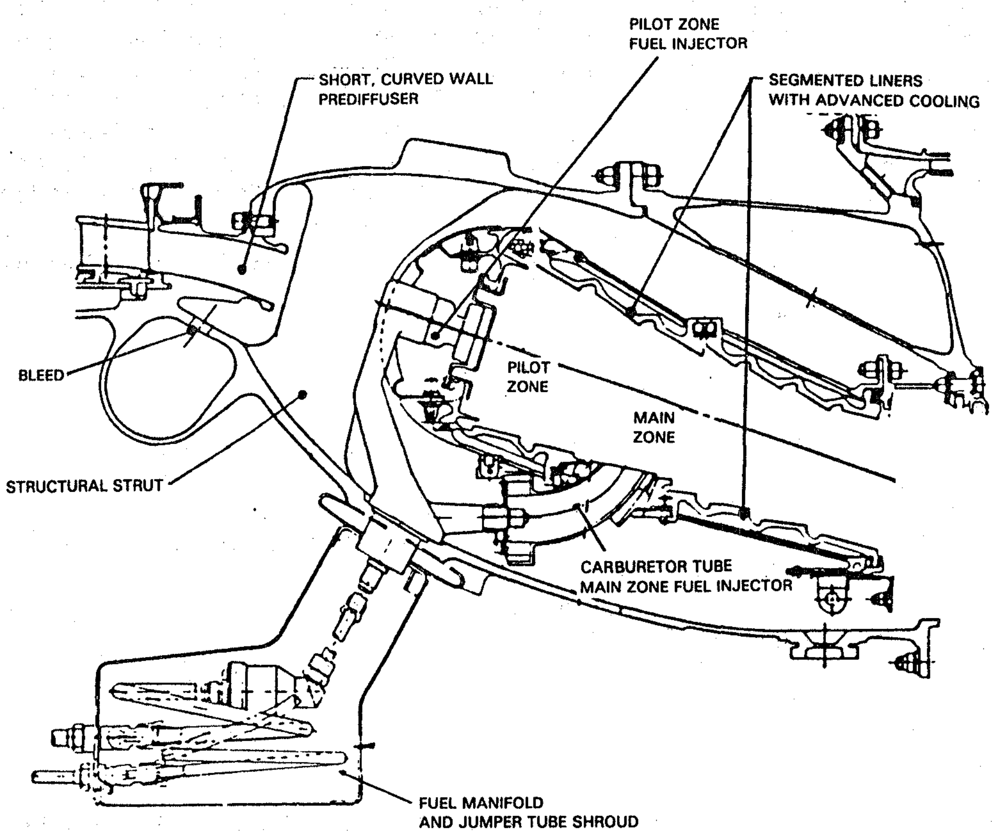


Figure 3.1-1 Energy Efficient Engine Combustor Design and Features

In the Sector Combustor Rig Test Program, the test vehicle used for demonstrating and refining the advanced features is a 90-degree circumferential sector of the full annular Energy Efficient Engine combustor component. The 90-degree test section, although imposing certain limitations when compared to a full annular test configuration, is a developmental tool that provides an expedient and low cost approach to evolve design improvements before the component is tested in full scale. The rig has the capability to operate in the environment anticipated for the combustor component to realistically assess aerothermal performance, emissions, safety, and mechanical characteristics.

Two rig configurations were designed and tested. The first had a conventional sheet metal louvered liner and was used primarily to optimize performance and emissions. The second incorporated the advanced segmented liner construction.

The following Section 3.2 presents a discussion of the sector rig design goals and requirements. Section 3.3 contains a description of the test rig configuration. A synopsis of the combustor aerodynamic and thermal-mechanical designs is presented in Sections 3.4 and 3.5.

3.2 DESIGN GOALS AND REQUIREMENTS

The performance and emissions goals established for the Energy Efficient Engine combustor component were adopted for the sector combustor rig design. The key goals are enumerated in Table 3.2-I. The goal for mechanical performance was no cracking or thermal distress such as buckling, while maintaining liner temperatures within the defined limits. A rig design requirement was for easy access to both the combustor and flowpath to minimize the time and cost for incorporating modifications. Design procedures conformed to standard Pratt & Whitney Aircraft design practices, since the test program involved testing at full Energy Efficient Engine sea level takeoff pressure and temperatures.

TABLE 3.2-I
COMBUSTOR PERFORMANCE AND EMISSIONS KEY GOALS

Pattern Factor (max)	0.37
Section Pressure loss, % (max)	5.5 of total pressure at Station 3
Exhaust Emissions (max):	
Hydrocarbon*	0.4
Carbon Monoxide*	3.0
Oxides of nitrogen*	3.0
Smoke, SAE No.	20.0

*Environmental Protection Agency Parameter (pound pollutant/1000 pounds-thrust hour/cycle)

3.3 GENERAL RIG CONFIGURATION

The sector combustor rig is designed with numerous features to enhance test flexibility, while ensuring component simulation. The test rig design provides rapid mount and disconnect from the test facility. A cross-sectional view of the sector rig is shown schematically in Figure 3.3-1. Basically, the rig is comprised of two main modular elements: the inlet and diffuser/combustor test sections.

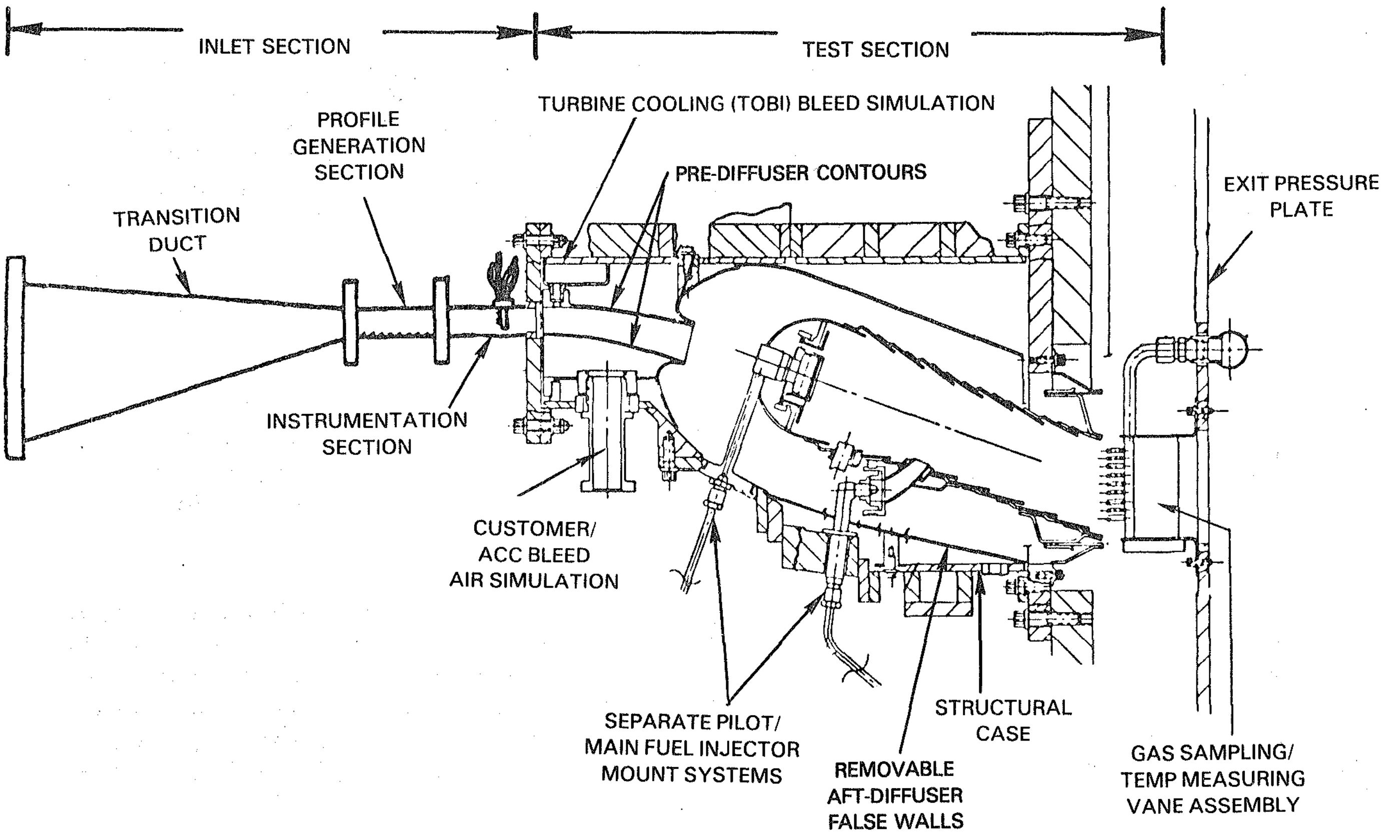


Figure 3.3-1 Sector Combustor Rig Design Features

The inlet section contains a transition duct, which adapts the facility air supply duct to the sector rig inlet. For test flexibility, this section also contains a removable pressure profile generator to permit testing with profile perturbations to simulate various compressor discharge profiles without removing the rig from the test facility.

The test section is a sector of the Energy Efficient Engine diffuser and two-stage combustor, containing all of its technology features and geometrical characteristics. However, there are some slight differences between the sector and engine component designs to enhance test flexibility. For example, the test section represents a 90-degree sector of the full annular section at the diffuser inlet, but the actual combustion section (to the side walls) is limited to a nominal 80-degree sector of the full annular configuration. The excess flow area at the inlet, equivalent to 10 degrees of the arc, provides a channel for cooling flow to the combustor side walls.

The rig is a modular design to facilitate possible variations of prediffuser or aft-diffuser contours, diffuser case strut geometry, and combustor zone geometries. The fuel injector support designs permit independent changes to the pilot and main zone fuel injectors. Simulated tangential on-board injection (TOBI) bleed at the prediffuser inlet, customer service and active clearance control bleed, and inner/outer shroud features have been incorporated to provide an accurate simulation of airflow and pressure distribution into the combustor section.

Either traversing or stationary instrumentation rakes can be installed at the combustor exit plane to record pressure and temperature distributions and collect exhaust emissions samples. Besides this exit instrumentation, the rig inlet and diffuser/combustor sections contain a variety of sensors to monitor performance, liner temperatures and operational safety. Information pertaining to test instrumentation is contained in Section 4.3.

3.4 RIG AERODYNAMIC DESIGN

3.4.1 Diffuser Section

The diffuser system consists of a prediffuser, a dump region, and inner and outer annuli. These parts are designed to minimize pressure loss and flow instabilities. The aerodynamic definition of this component is based on the results acquired from the Energy Efficient Engine Diffuser/Combustor Model Test Program (Ref. 1).

As shown in Figure 3.4.1-1, the prediffuser has a strutless, curved-wall flowpath. This type of design is necessary to offset the large difference in radii between the high-pressure compressor exit and high-pressure turbine inlet. To reduce the pressure losses associated with flow turning around the front end of the combustor, the flow is directed outward and closely aligned with the combustor centerline. The prediffuser has an area ratio of 1.5, with a length to inlet height ratio of 3.5.

The dump region, immediately downstream of the prediffuser, contains the structural struts, which connect the inner and outer combustor cases. The struts are thin and aerodynamically shaped to minimize the impact of trailing edge wakes on the combustor and provide a dump gap ($X/\Delta R$) that is acceptable in terms of diffuser flow pressure loss and stability considerations. Also, the annular shroud areas between the structural case and liners are sized to minimize pressure loss as well as prevent aspiration of hot combustion gases.

3.4.2 Combustor

As illustrated in Figure 3.4.2-1, the combustor has two distinct burning zones: a pilot zone and a main combustion zone, The pilot zone operates at all flight conditions. It is designed to minimize emissions at idle, plus provide adequate stability and relight characteristics. The main zone is operative at conditions above idle. In this zone, lean combustion minimizes emissions of smoke and oxides of nitrogen at high power. The combined operation of these zones provides emissions control through the entire flight spectrum.

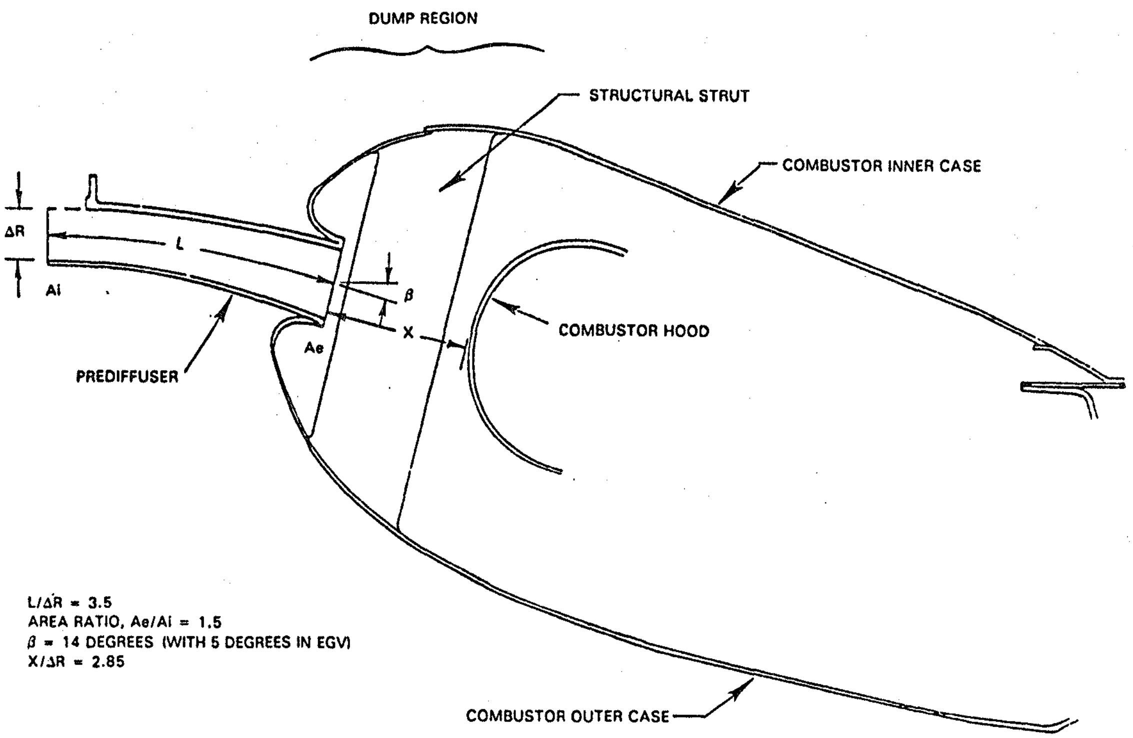


Figure 3.4.1-1 Sector Rig Diffuser Characteristics

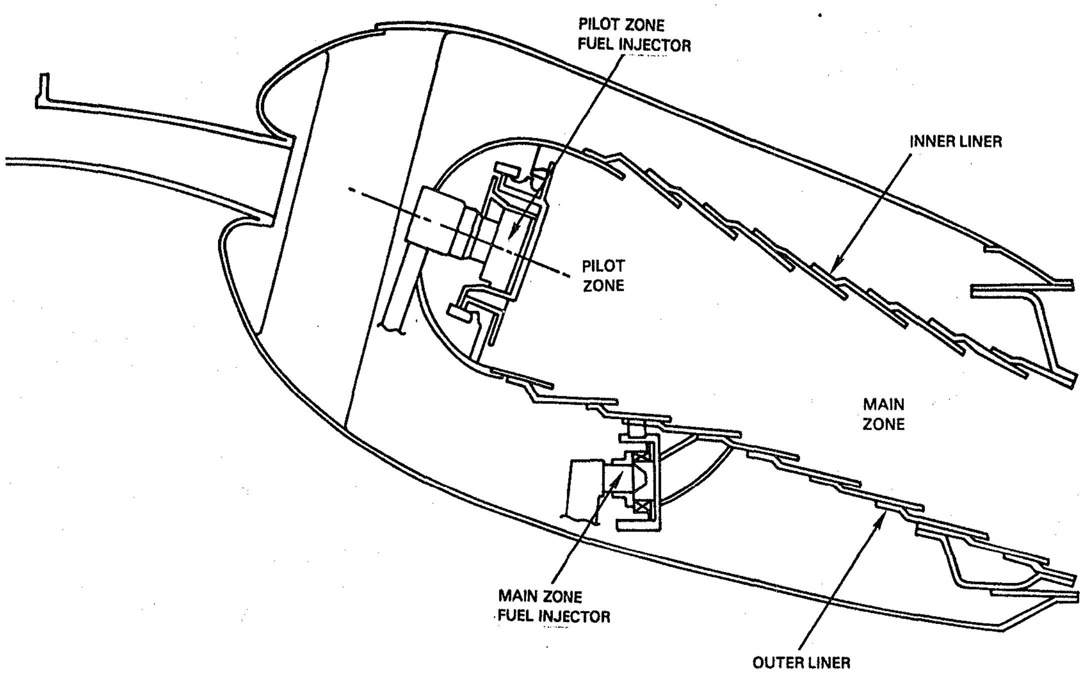


Figure 3.4.2-1 Features of Sector Rig Combustor with Louvered Liners

Table 3.4.2-I identifies some of the parameters governing the aerodynamic definition of the pilot and main combustion zones. In comparison to the combustor designed under the NASA-sponsored Experimental Clean Combustor Program, which is the precursor to this design, the heat release rate from the pilot zone is considerably lower. This results in lower reference velocities and longer residence times, both of which are conducive to lower carbon monoxide and unburned hydrocarbon emissions. Another characteristic is the increase in dome height. This provides a larger recirculation zone for better relight and starting, and enhances the capability to reduce emissions at idle. A pilot zone equivalence ratio near 1.2 is maintained at idle power conditions.

TABLE 3.4.2-I
AERODYNAMIC DESIGN PARAMETERS

	PILOT ZONE
Length, cm (in)	11.9 (4.7)
Dome Height, cm (in)	9.3 (3.7)
Fuel Injector Spacing, cm (in)	7.8 (3.1)
Pilot Zone Heat Release Rate, (Btu/ft^3 atm hr)	7.5×10^6
Ref. Velocity, m/sec (ft/sec)	6 (20)
Residence Time, (msec)	18
MAIN ZONE	
Length, cm (in)	16.0 (6.3)
Height, cm (in)	6.6 (2.6)
Fuel Injector Spacing, cm (in)	4.64 (1.83)
Ref. Velocity, m/sec (ft/sec)	32 (106)
Residence Time (msec)	4.5

In the definition of the main zone, the residence time was decreased approximately 10 percent relative to the Experimental Clean Combustor Program design for better control of oxides of nitrogen. The main zone equivalence ratio predicted for sea level takeoff is approximately 0.7.

The combustor flow distribution, as analytically defined, is presented in Figure 3.4.2-2. Nearly 88 percent of the total diffuser exit flow is used for combustion air and liner cooling flow, with the remaining 12 percent used for turbine cooling. Approximately 10 percent of the combustor airflow is used for pilot zone combustion air, while about 28 percent is used for main zone combustion air. Further definition of the airflow distribution evolved during rig testing is discussed in Section 5.0.

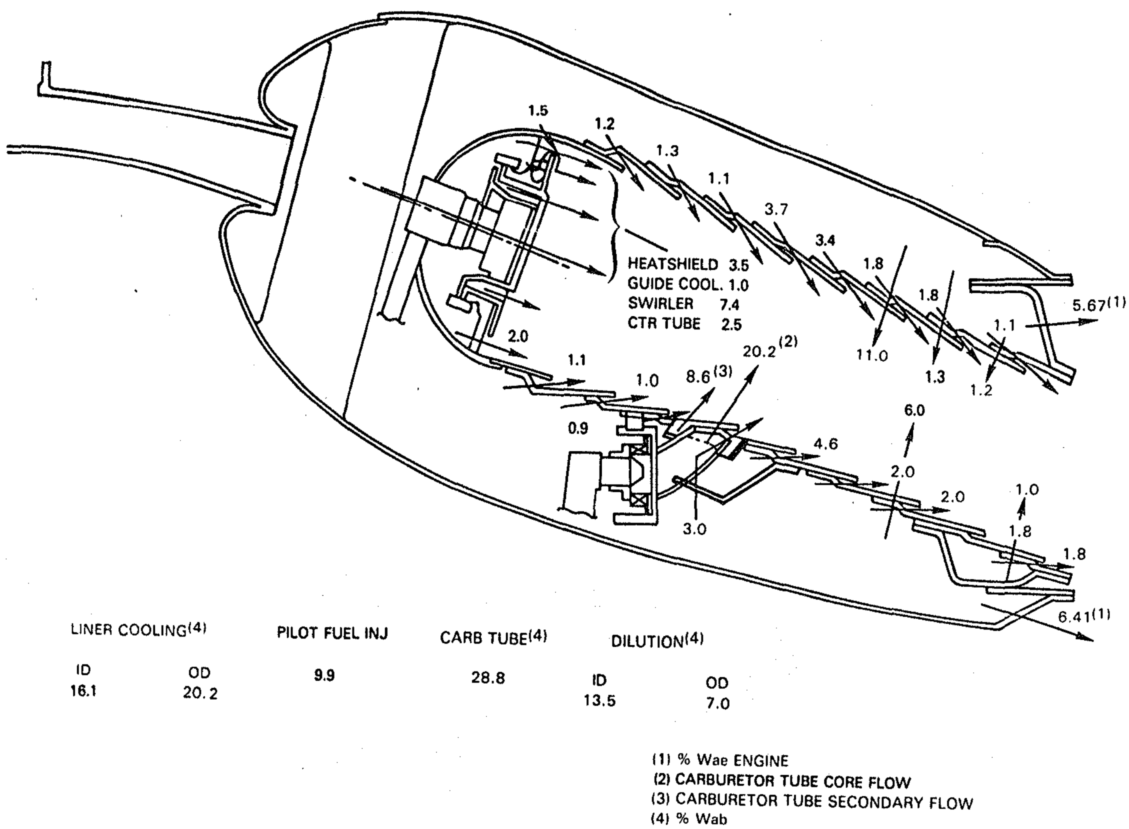


Figure 3.4.2-2 Sector Rig Flow Split and Distribution

The liner for the combustor component is an advanced design, using segmented construction and counter-parallel FINWALL® as the cooling approach. This type of liner configuration was dictated by the life goal of 8000 hours and a liner cooling airflow limit of 35 percent of combustor airflow. This limit was established to ensure an adequate air supply for dilution and emissions control. Although the advanced liner design was incorporated into the second sector rig configuration, a sheet metal louvered liner was successfully used as a low cost developmental tool during the early phases of testing to optimize combustor air management and flow splits.

Figure 3.4.2-3 shows the counter-parallel FINWALL® cooling scheme. This method is an advanced convective/film cooling technique that maximizes heat transfer capability with a minimum amount of air. Airflow enters through slots in the cold wall and flows upstream and downstream in discrete cooling passages. The coolant is then discharged on the hot side to form an additional protective film. The design maximum liner metal temperature is 1010°C (1850°F). The combustor liners are designed with a 2.5-percent pressure loss to ensure positive turbine cooling supply pressure.

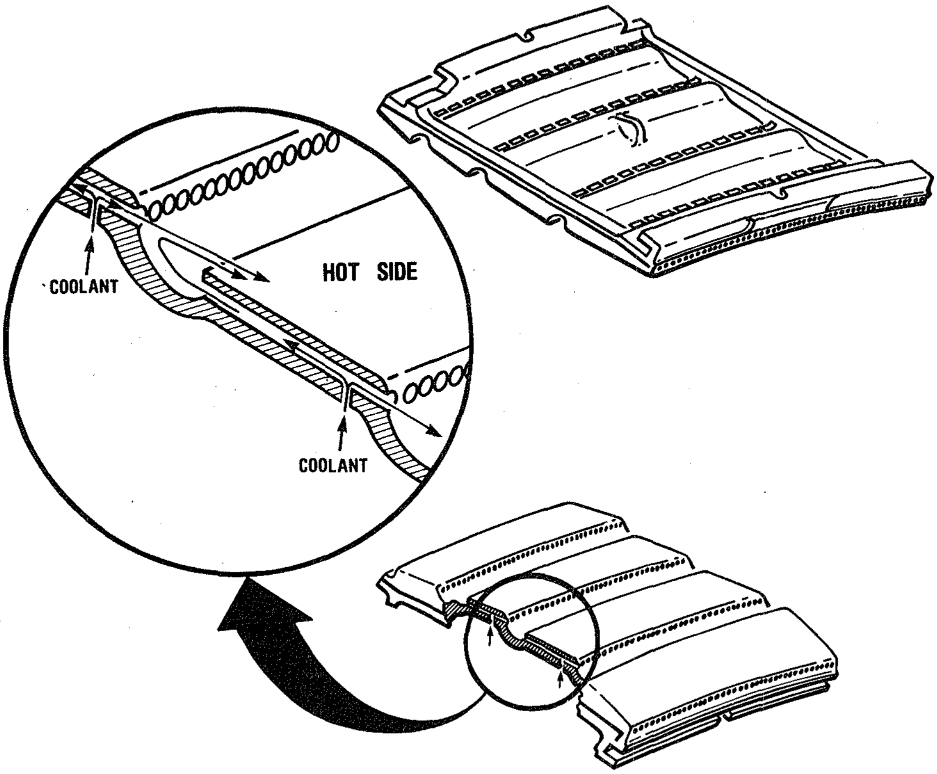


Figure 3.4.2-3 Counter-Parallel FINWALL® (CPFW) Cooling Scheme

3.5 RIG THERMAL-MECHANICAL DESIGN

3.5.1 Diffuser Case

The mechanical design of the sector rig diffuser is presented in Figure 3.5.1-1. As indicated, the prediffuser flowpath is void of any structural struts. In the engine component design, structural support for the inner and outer cases is provided by 24 struts in the dump region. A duplicate of the strut configuration, emanating from the component preliminary design, was incorporated into the sector rig diffuser section design.

In the rig, the primary function of these struts was not structural support, but accurate aerodynamic simulation of those required for structural support in the combustor component. As the design of the combustor evolved, it became necessary to modify the strut design, as shown in Figure 3.5.1-2, to provide adequate stiffness for the support structure. Testing of this design during the Diffuser/Combustor Model Test Program indicated that the downstream effects of the geometry were minimal. Therefore, the rig strut design was not modified. Aside from this small difference, all other diffuser characteristics of the engine combustor component were accurately simulated in the rig design.

3.5.2 Combustor Section

The combustor section in the test rig includes the front-end subassembly, liners, carburetor tubes and fuel injection system. These are described in the following section.

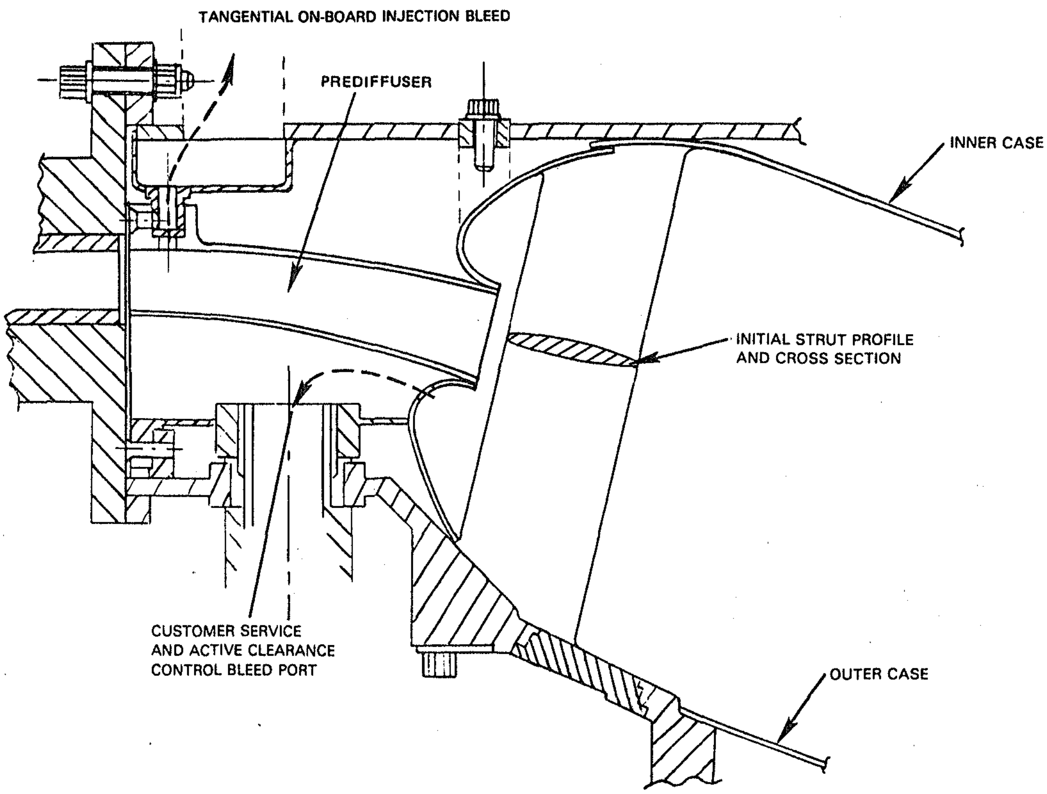


Figure 3.5.1-1 Sector Combustor Rig Diffuser Section Mechanical Design

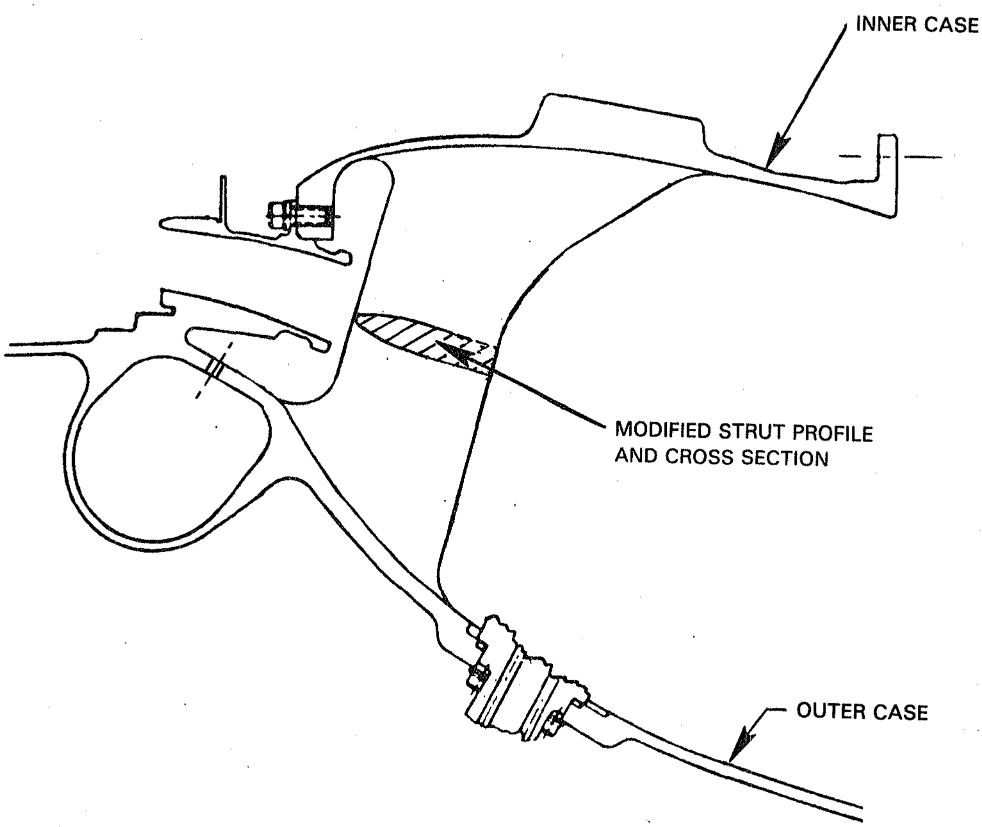


Figure 3.5.1-2 Energy Efficient Engine Combustor Component Diffuser Section Showing Modified Strut Design

3.5.2.1 Combustor Front-End Subassembly

The front-end subassemblies for the louvered and segmented liner configurations are illustrated in Figure 3.5.2-1. The primary elements of these subassemblies are the hood, bulkhead, mount pin supports, pilot zone fuel nozzle guide, and heatshield.

Common to both front end subassembly configurations was the mount pin scheme shown in Figure 3.5.2-1. The bulkhead for the segmented liner configuration also contains provisions for structural support of the outer liner segments and segment support structure.

The pilot zone fuel injector guides are attached to the bulkhead by retaining clips. These clips are positioned in slots to allow for the radial movement required for assembly and thermal expansion as well as to prevent guide rotation.

3.5.2.2 Combustor Liners

As mentioned previously, both a conventional louvered liner and an advanced segmented liner were tested in the sector rig. Combustion sections utilizing these liners were designed to a common reference length (L_{ref}) so that the test section length would not have to be changed to accommodate either configuration.

Conventional Louvered Liners

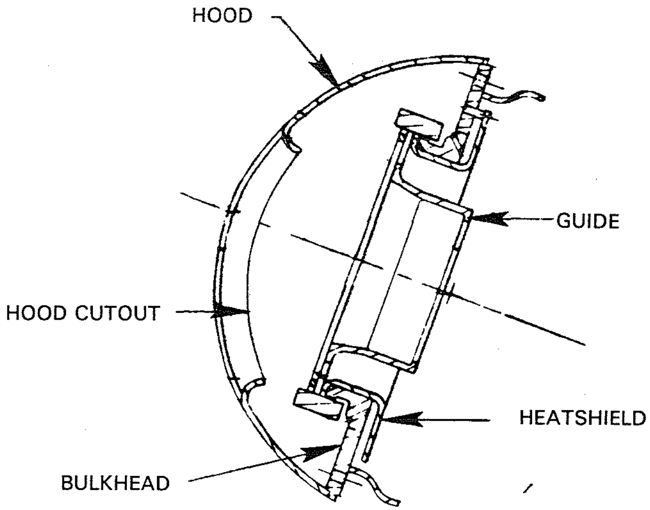
The louvered liner design used in the majority of the sector rig tests is illustrated in Figure 3.5.2-2. The design had the same cooling level required for the engine combustor component.

The louvered construction is similar to that used in the combustion systems of current Pratt & Whitney Aircraft commercial and military gas-turbine engines, including the JT9D-7A reference engine. The liner material is Hastelloy X sheet metal, and the louver sections are resistance-welded together. Although Hastelloy X material is suitable for experimental rig testing at reduced pressures, it would not have adequate life in the Energy Efficient Engine.

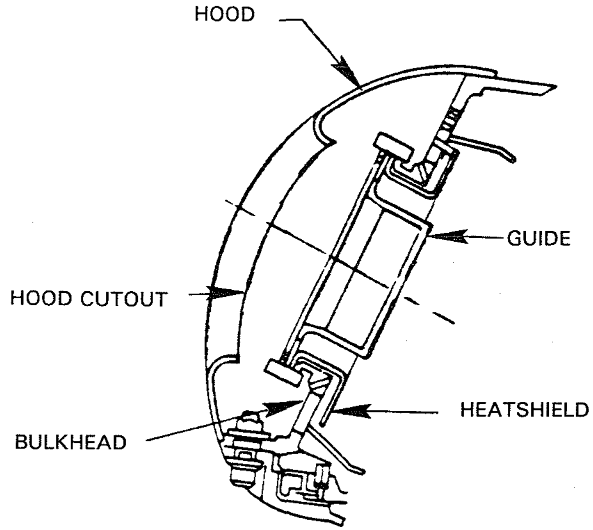
The design maximum liner temperature is 982°C (1800°F) at 0.2 percent yield strength for Hastelloy X material. The maximum bending stress was found to be at the exit end of the outer liner. A hat section (Figure 3.5.2-2) was welded to the liner at this section to maintain acceptable stress levels. Provisions for mounting the main zone carburetor tubes and fuel injectors are in the outer liner. Both inner and outer liner are welded to the bulkhead.

Advanced Segmented Liners

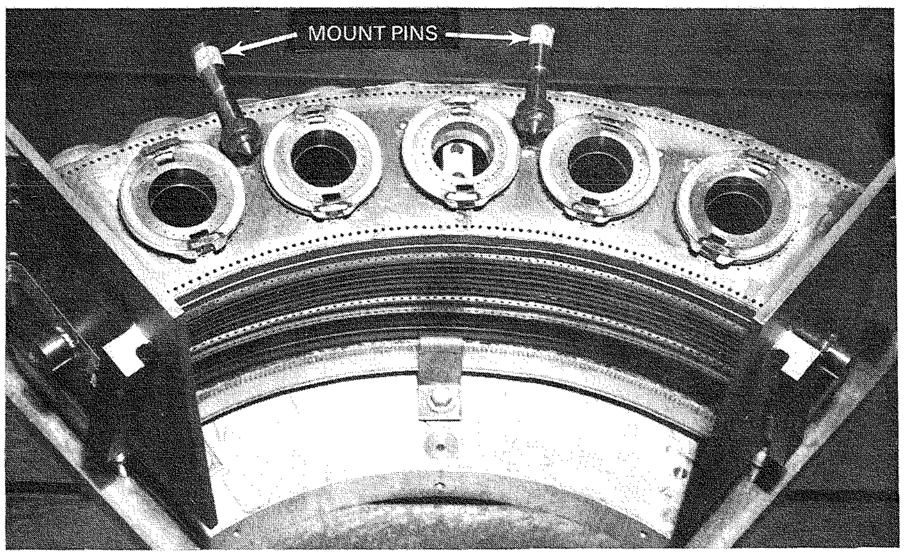
The mechanical design of the segmented liner is illustrated in Figures 3.5.2-3 and 3.5.2-4. Basically, the liner consists of individual segments attached to support frames. The segments range in length from approximately 11.10 cm (4.375 in) up to 13.34 cm (5.250 in) and in width from approximately 8.73 cm (3.4375 in) up to 11.17 cm (4.5625 in). The inner and outer liners are formed by arranging segments circumferentially in both the pilot and main zones to create the gas path. Provisions for main zone carburetor tubes and fuel injectors are incorporated in the outer front segments.



(a)
FRONT-END DESIGN FOR SHEET METAL LOUVER LINER CONFIGURATION



(b)
FRONT-END DESIGN FOR SEGMENTED LINER CONFIGURATION



(c) FRONT-END VIEW OF COMBUSTOR RIG (HOOD REMOVED)

Figure 3.5.2-1 Sector Combustor Rig Front-End Subassemblies

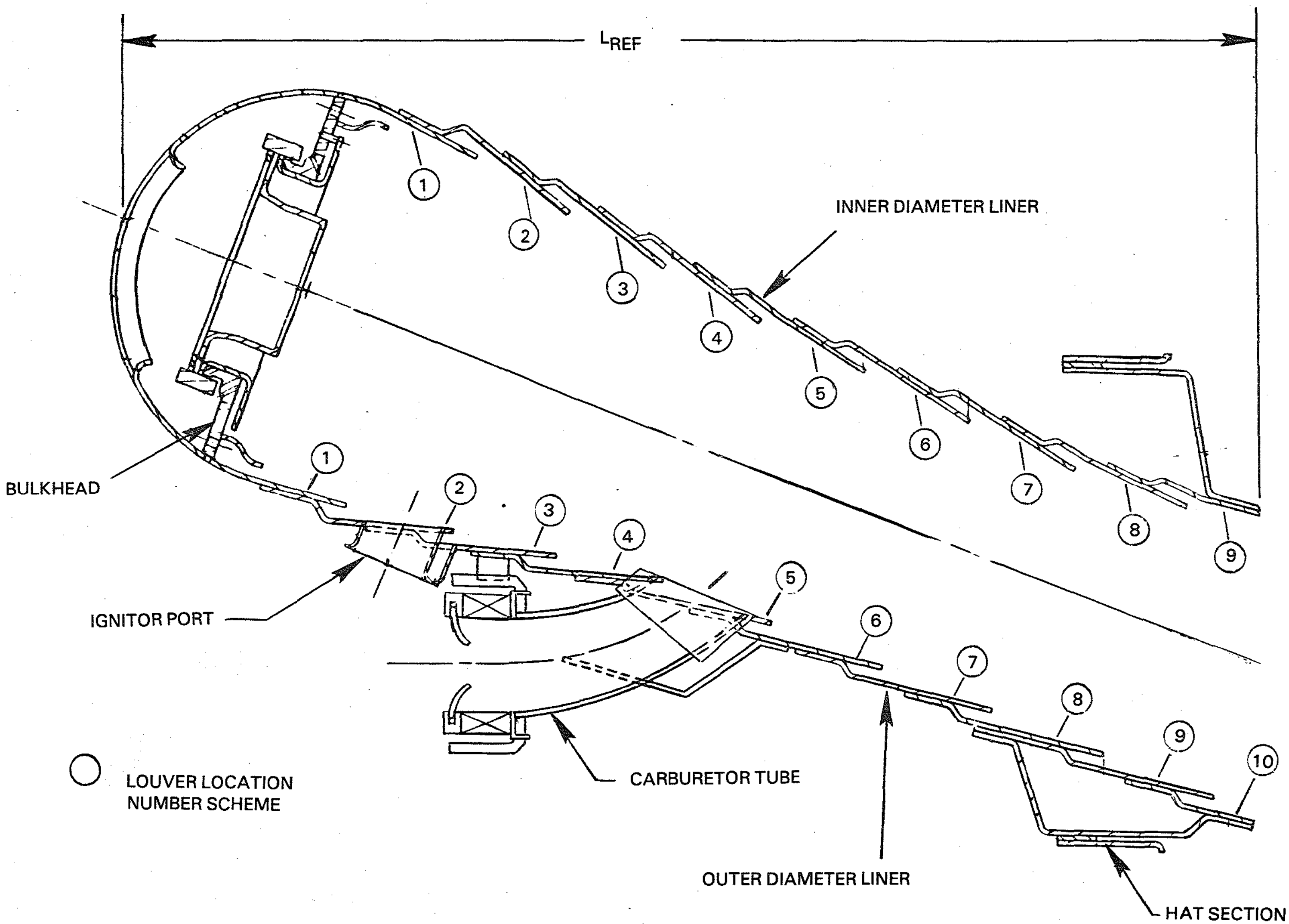


Figure 3.5.2-2 Conventional Sheet Metal Louver Liner Design

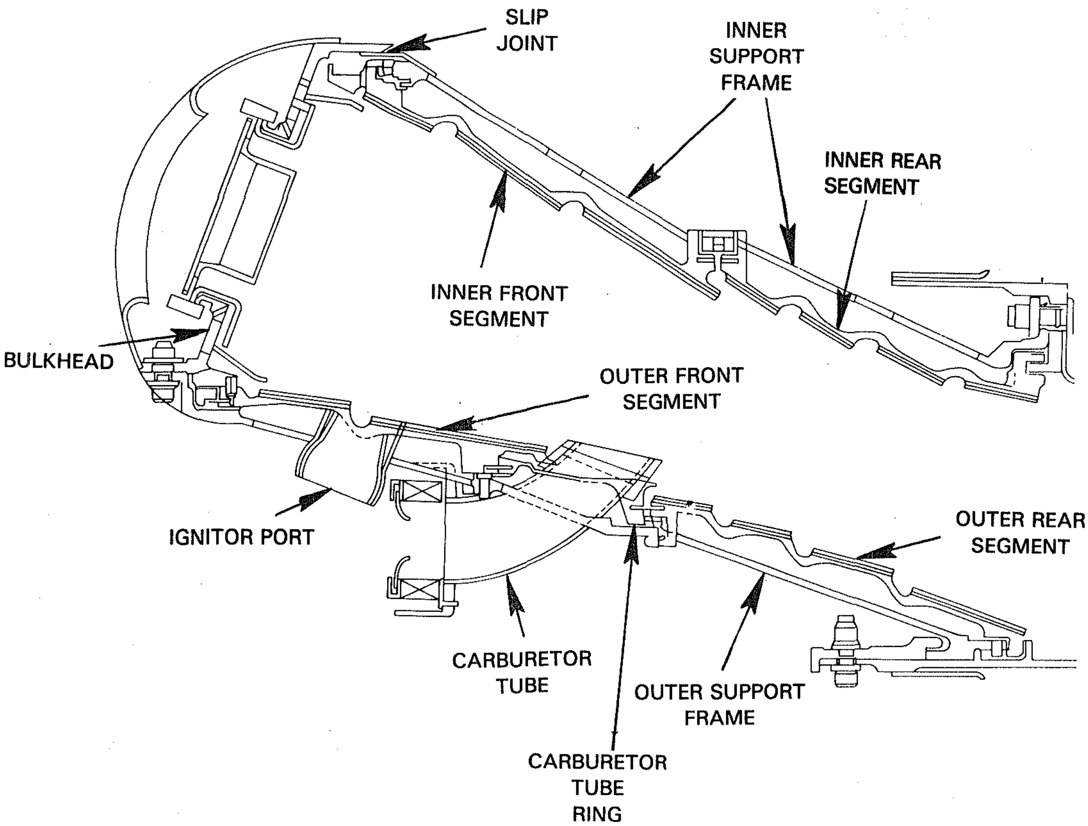


Figure 3.5.2-3 Advanced Segmented Liner Design

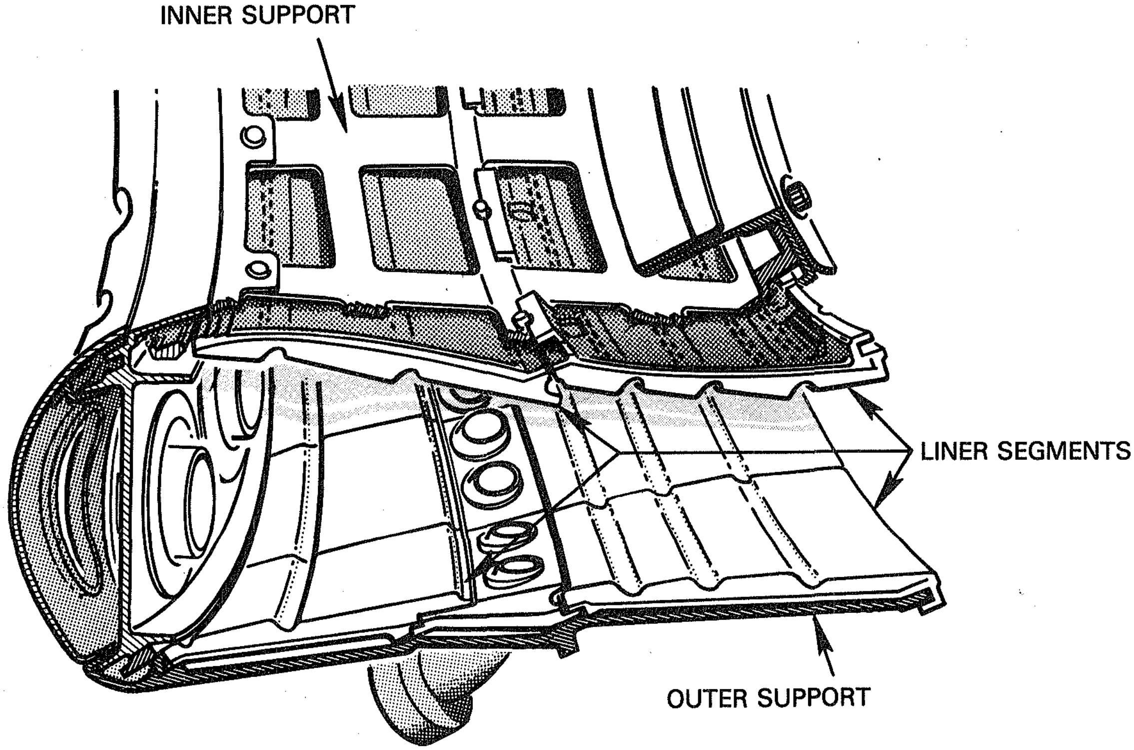


Figure 3.5.2-4 View of Segmented Liners and Liner Support Frames

The front section of the outer support frame is bolted to the bulkhead subassembly, whereas the rear section is attached by a hook arrangement, as illustrated in Figure 3.5.2-3. The inner support structure is bolted to the case at the rear, but mates to the bulkhead subassembly through a slip joint that accommodates thermal growth in the liner segment support structure.

To attach each liner segment to the support frame, hooks on the back of the segment mate with circumferential rails on the structural support framework. Axial and circumferential feather seals are used to control leakage between abutting segments. Figure 3.5.2-5 presents a typical liner segment showing the hook and feather seal slot arrangement. The circumferential feather seals between carburetor tube panel and both outer front and outer rear liner segments can be seen in Figure 3.5.2-6.

The segments are cast from B1900 + Hf turbine alloy, while the support frame is manufactured from Hastelloy X (AMS 5754) nickel base alloy. This liner system offers a predicted life of 11,700 hours for the engine combustor component, which exceeds the design goal of 8000 hours.

3.5.2.3 Carburetor Tubes

The carburetor tube design characteristics evolved from the fuel injector characterization tests described in Section 4.1.1. Figure 3.5.2-6 compares typical features of the designs for the louver and segmented liner rig configurations. Both designs feature floating nozzle guides to accommodate relative displacement between the carburetor tube and the main zone fuel injector. Also each incorporates radial inflow swirlers to facilitate mixing of fuel and air.

The main difference between the two configurations is the mount structure. In the louvered design, the carburetor tube radial inflow swirler case is fastened directly to the liner structure with a sheet metal weldment. A sleeve, integral with the liner, supports the carburetor tube at the exit plane.

The mount structure for the segmented design is somewhat different. The radial inflow swirler case is bolted to the segmented liner outer support structure. The carburetor tube exit support is a sleeve insert mounted between the front and rear outer liner segments.

3.5.2.4 Fuel Management System

The combustor fuel management system consists of the fuel manifolding, fuel injector support assemblies and fuel injectors. The design for the combustor component is shown in Figure 3.5.2-7. The design features a multi-support fuel injector that combines one pilot zone support arm with two main zone support arms in a clustered arrangement on a common base. With this configuration, 24 aerated fuel injectors are employed in the pilot zone and 48 carburetor tube injectors in the main zone.

The sector rig pilot zone and main zone fuel injectors, however, are mounted separately, as indicated in Figure 3.5.2-8. This facilitated installation and removal of injectors as modifications evolved during the program. Separate fuel supply sources were employed for the same reason.

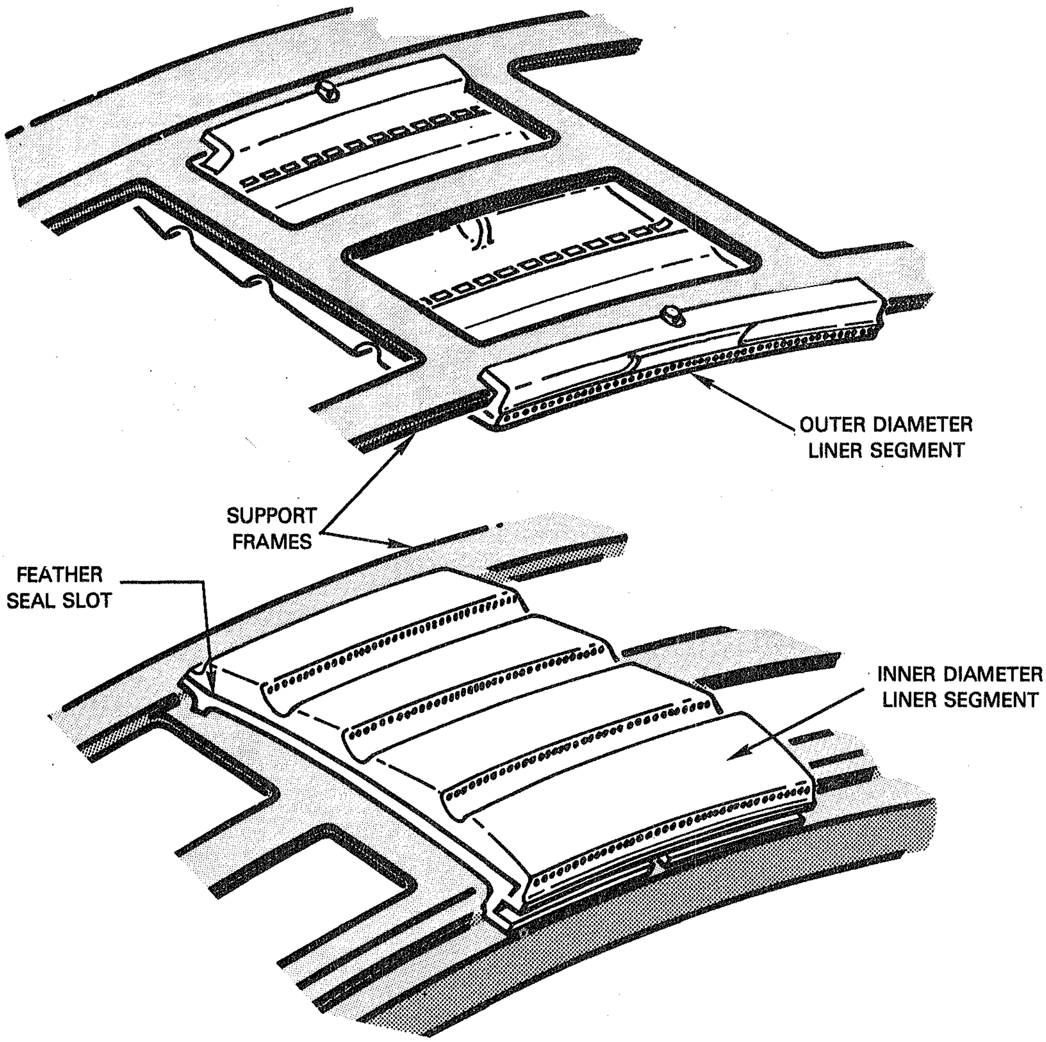


Figure 3.5.2-5 Typical Liner Segments

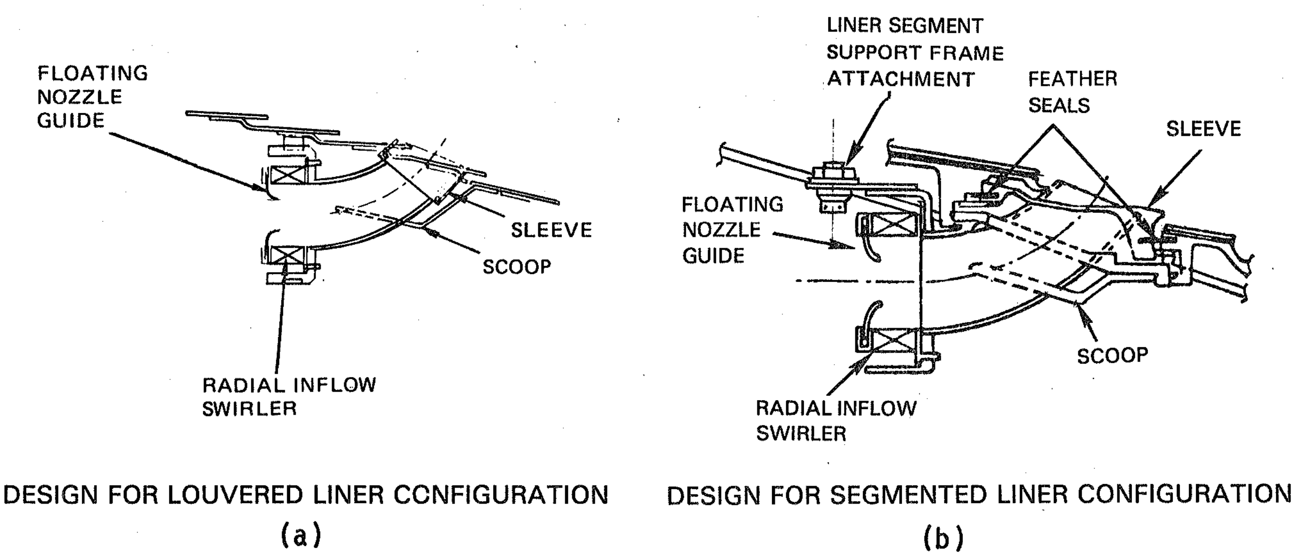


Figure 3.5.2-6 Carburetor Tube Designs for Louvered Liner and Segmented Liner Combustor Configurations

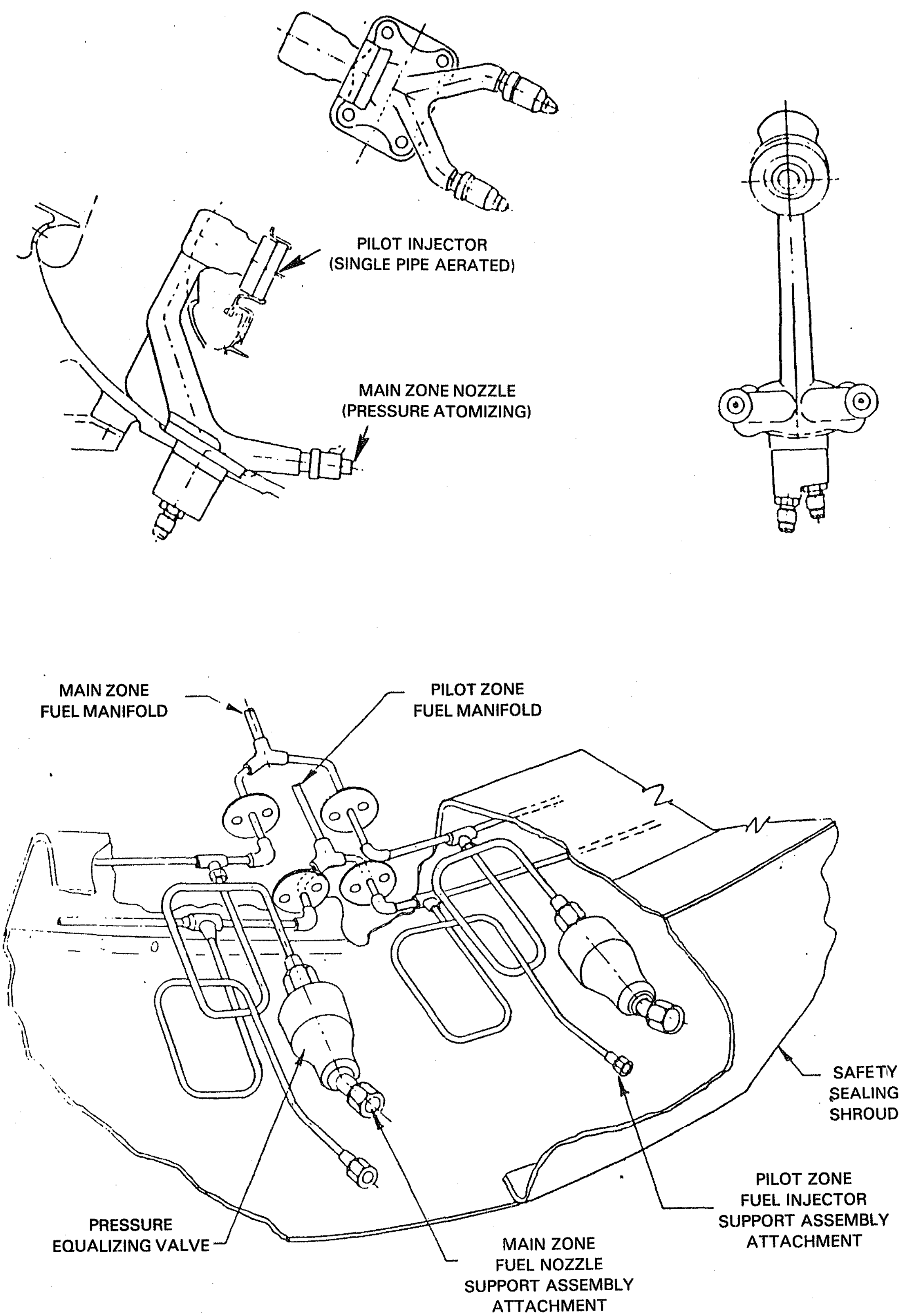


Figure 3.5.2-7 Flight Propulsion System Fuel System Characteristics

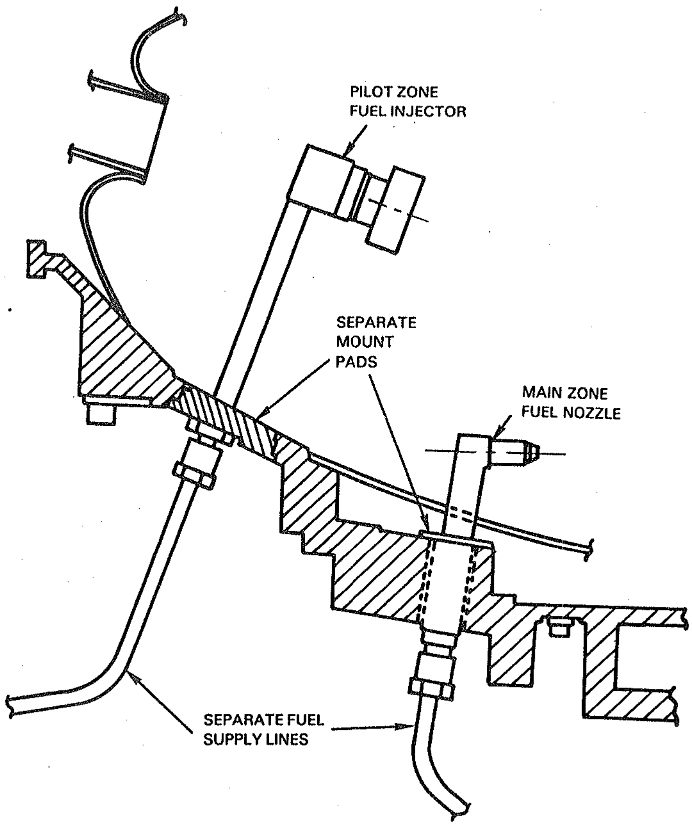


Figure 3.5.2-8 Sector Rig Fuel System Design

3.6 SECTOR COMBUSTOR RIG FABRICATION AND ASSEMBLY

Fabrication of the various rig components, including the 90-degree sector of the combustor with both louvered and segmented liners, was performed using conventional manufacturing methods. Manufacturing tolerances were in conformance with Pratt & Whitney Aircraft's standard practices for the manufacture of test components and adapting hardware.

The louvered liner sector combustor rig is shown during fabrication in Figure 3.6-1. After forming, the individual liners are resistance welded to produce the inner and outer liner subassemblies. These subassemblies are then welded to the bulkhead subassembly. Figure 3.6-2 shows the carburetor tube secondary air scoop being welded to the outer liners.

The advanced liner segments, which are an investment cast nickel base alloy (B1900 + Hf), required a series of different operations to final machining. Approximately 55 fixtures were necessary to complete the fabrication process.

The most prominent aspect of this fabrication effort was the simultaneous electro-chemical machining of a minimum of 50 counter-parallel FINWALL® cooling passages, which are 0.088 cm (0.035 in) in diameter. This was repeated several times for each segment, depending on the number of panels in each segment. Figure 3.6-3 shows a typical setup for electro-chemical machining the cooling holes. A three-panel segment with cooling passages installed is shown in Figure 3.6-4.

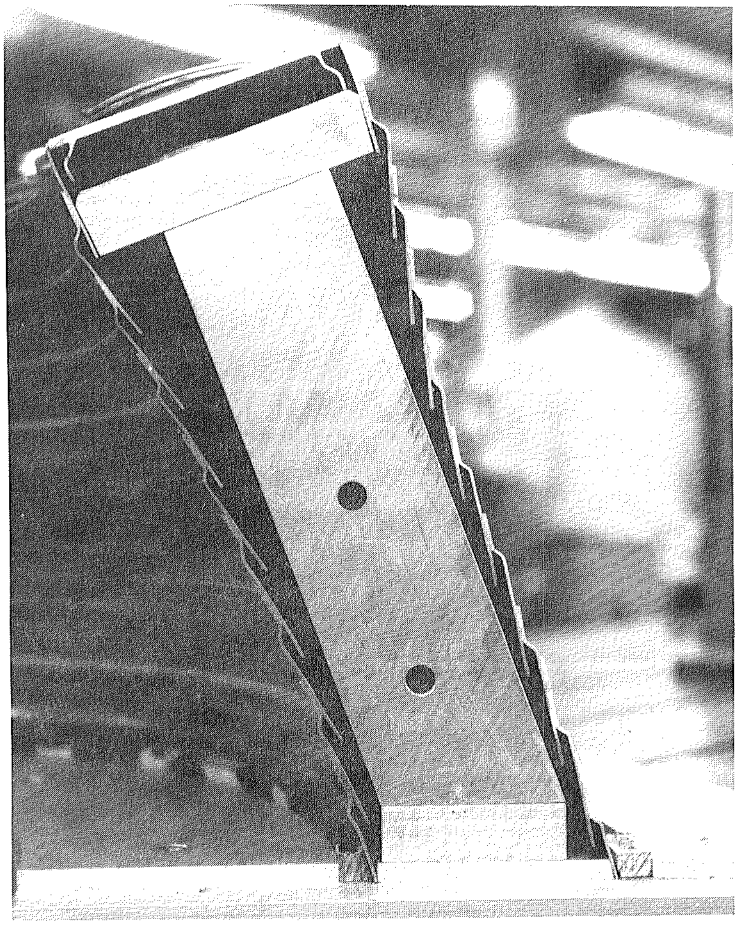


Figure 3.6-1 Sector Combustor Louvers During Assembly

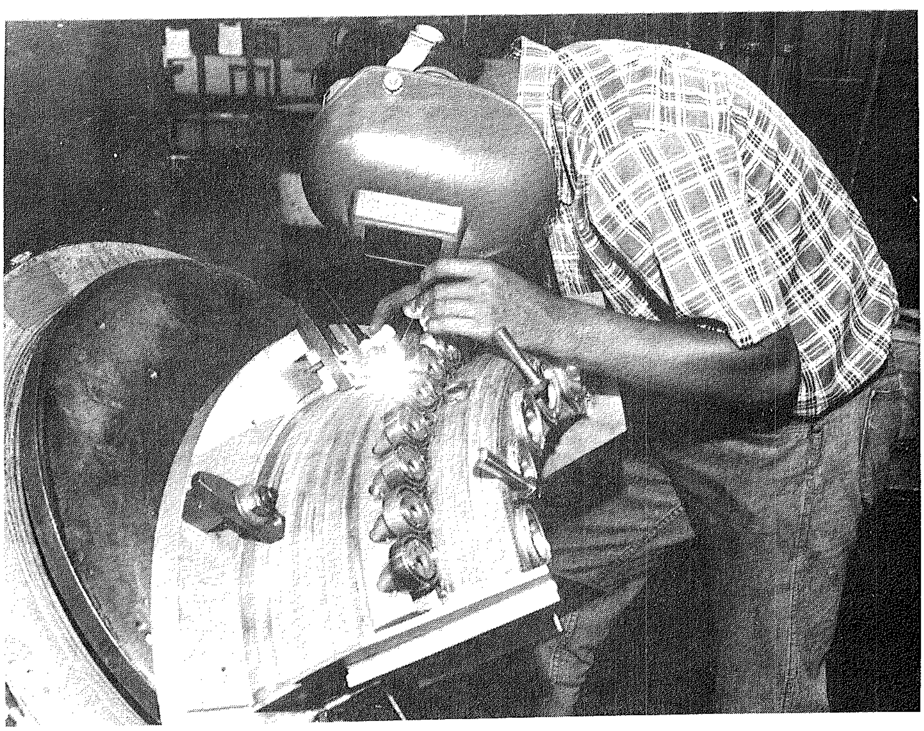


Figure 3.6-2 Welding of Carburetor Tube Secondary Air Scoop to Outer Liners

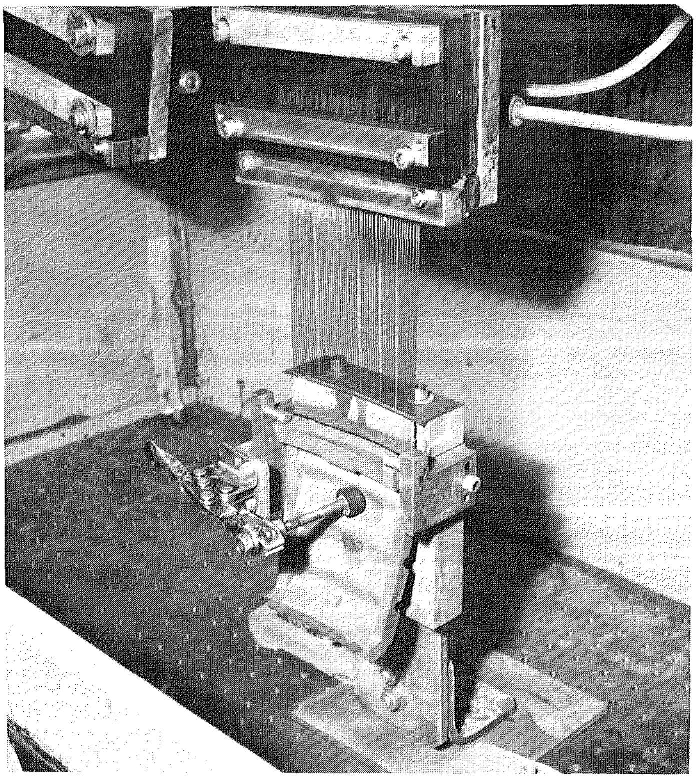


Figure 3.6-3 Typical Setup for Electro-Chemical Machining of Counter-Parallel FINWALL® Cooling Holes

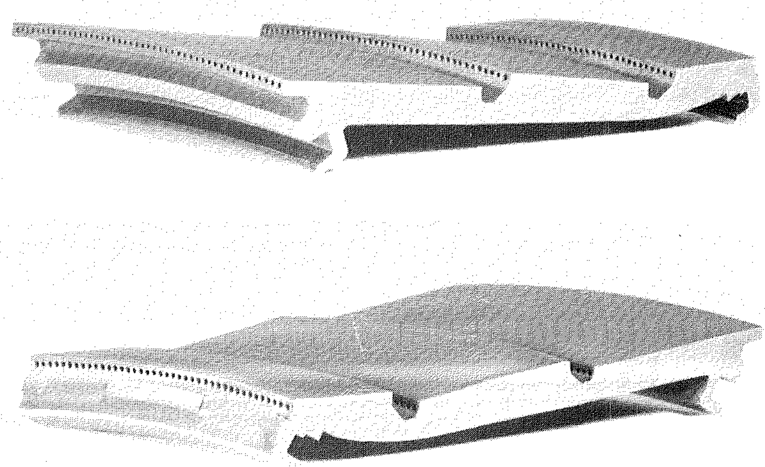


Figure 3.6-4 Liner Segment with Electro-Chemical Machined Cooling Holes (Segment total machining not complete)

Cooling air feed slots, which intersect the counter-parallel FINWALL® passages to supply cooling air from the cold side of the segment, were installed by electro-discharge machining. Installation of the attachment hooks was accomplished by conventional machining. Figure 3.6-5 shows a segment with the 0.444 x 0.152 cm (0.175 x 0.060 in) slots and hooks installed. Slots for the feather seals, which are used to minimize air leakage between adjacent segments, were also installed by electro-discharge machining. The setup for this operation is shown in Figure 3.6-6.

Following these steps, the segments were inspected for residual burr and flow checked to ensure proper flow characteristics.

Figures 3.6-7 through 3.6-10 show the sector combustor rig during the various phases of assembly. Figure 3.6-7 shows the liner segments installed on the inner support frame, illustrating the alignment of the feather seals. Figure 3.6-8 shows the liners and support frames attached to the bulkhead. In this figure, the combustor hood profile can be noted.

The pilot and main zone fuel injectors are shown in Figure 3.6-9. As discussed earlier, these injectors are different from the design used in the engine combustor component. The pilot aerating injector is illustrated on the top, and the details of the main zone carburetor tube are shown on the bottom. Figure 3.6-10 shows the completed combustor test section prior to installation in the rig case.

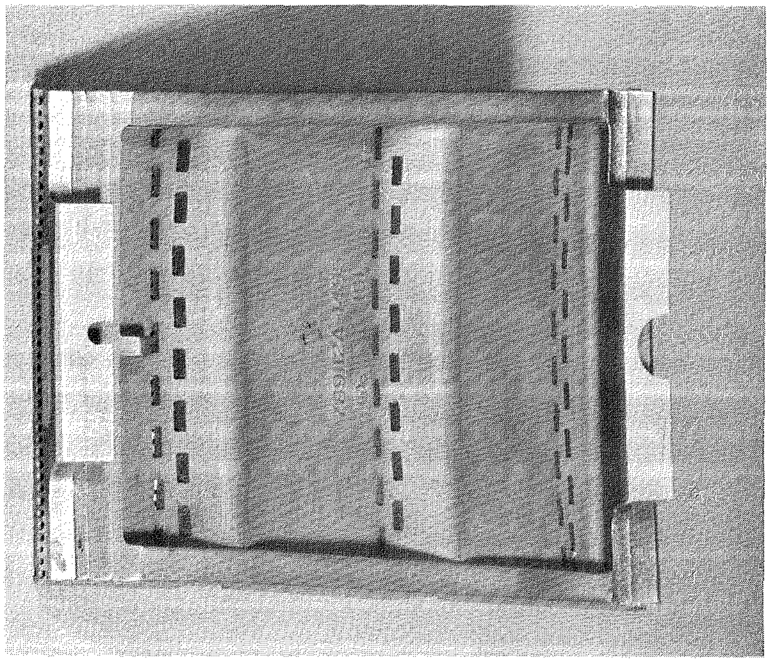


Figure 3.6-5 Completed Segment with Cold Side Feed Slots and Attachment Hooks Installed

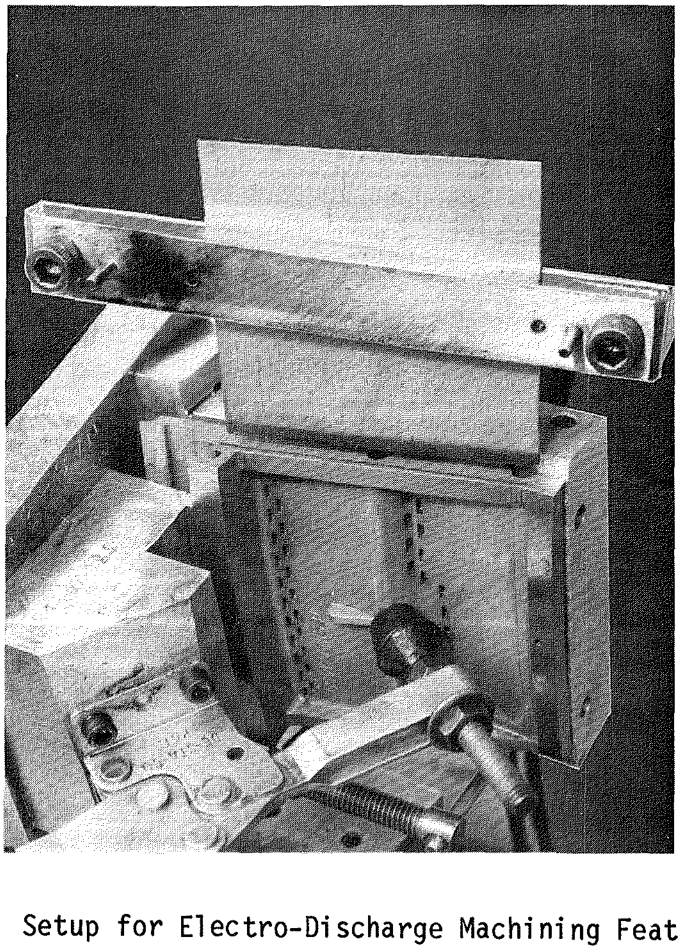


Figure 3.6-6 Setup for Electro-Discharge Machining Feather Seal Slots

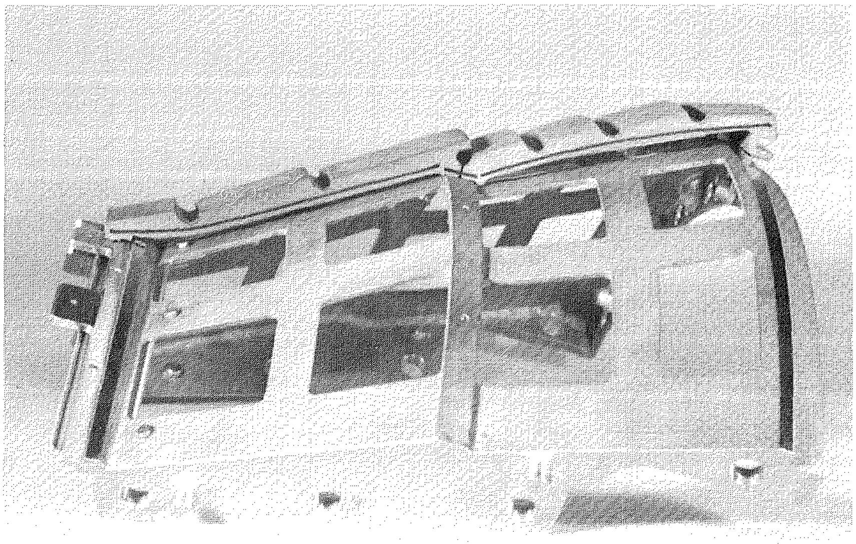


Figure 3.6-7 Liner Segments Installed on Inner Support Frame

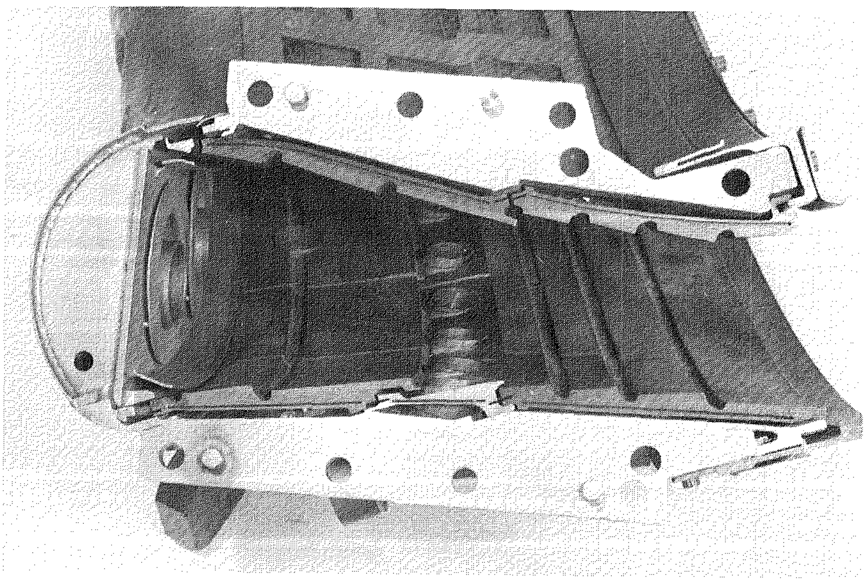
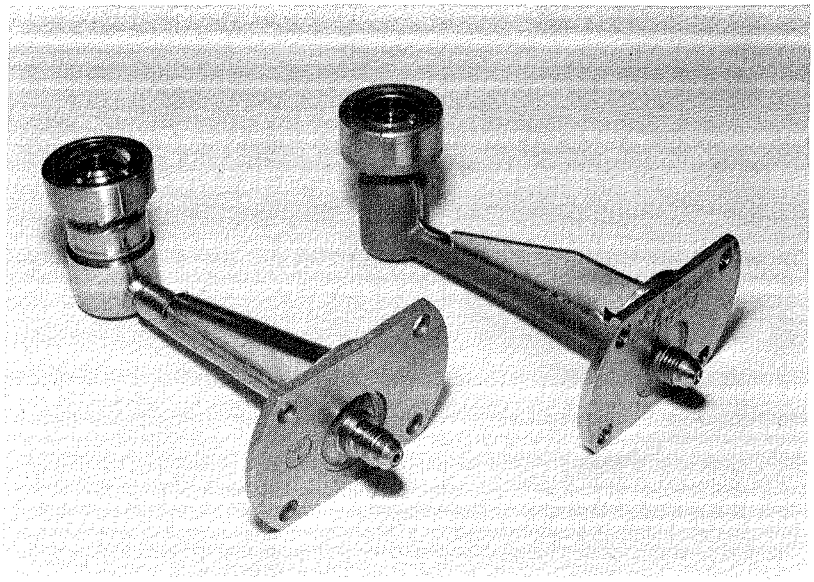


Figure 3.6-8 Sector Rig with Inner and Outer Liner Assemblies and Bulkhead/Hood Assembly in Place



PILOT ZONE

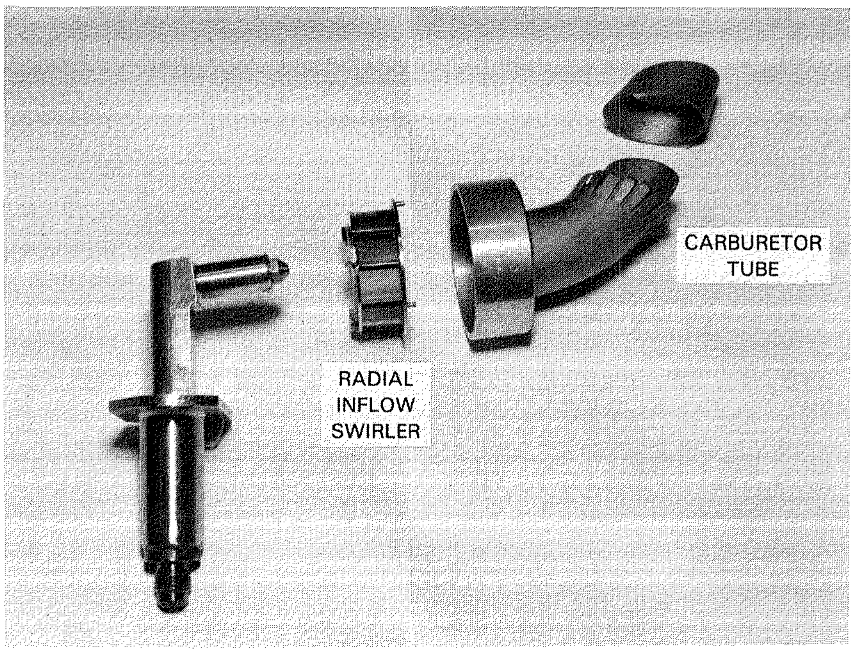


Figure 3.6-9 Sector Rig Fuel Injectors

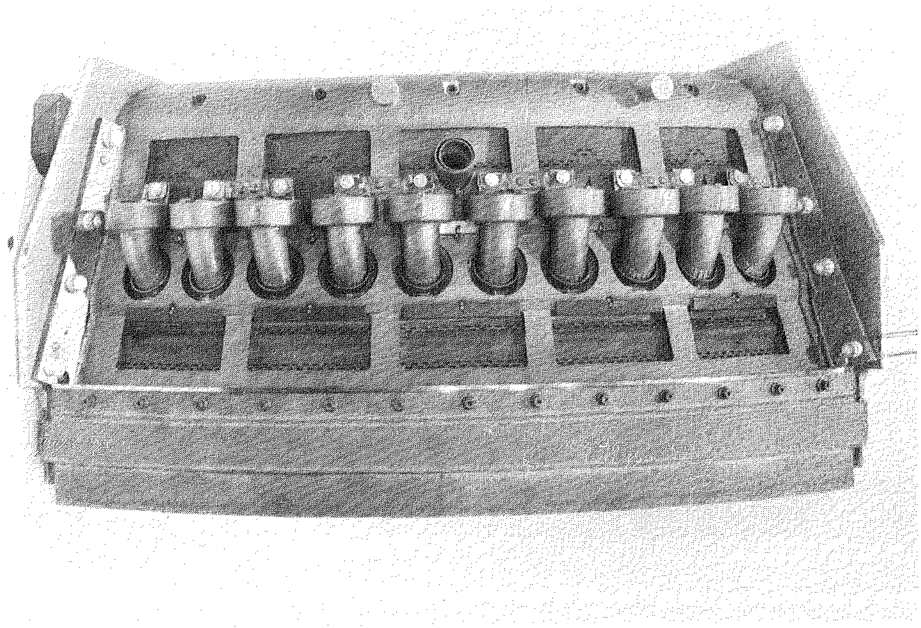


Figure 3.6-10 Completed Sector Combustor Rig Test Section

SECTION 4.0
TEST PROGRAM PLAN, FACILITIES AND INSTRUMENTATION

4.1 TEST PROGRAM OVERVIEW

The objective of the Sector Combustor Rig Test Program was to evaluate and refine the emissions, performance, structural integrity, and relight characteristics of the advanced two-stage combustor over the Energy Efficient Engine range of operation. Specific test goals are enumerated below.

Aerothermal Performance:	5.5 percent total pressure loss 0.37 pattern factor (max) Acceptable radial temperature profile Acceptable relight and lean blowout characteristics	
Emissions:	Hydrocarbons*	0.4
	Carbon monoxide*	3.0
	Oxides of nitrogen*	3.0
	Smoke, SAE number	20
Mechanical Performance:	No cracking or obvious thermal distress Acceptable thermal gradients and temperature streaks	

*Environmental Protection Agency Parameters (EPAP)

The program was structured to substantiate the advanced technology features required to satisfy these goals prior to the combustor component tests. Testing was organized into three separate phases. The first consisted of fuel injector characterization tests, which were performed prior to and during sector rig testing. The second phase comprised a series of performance and emissions optimization tests using the sector rig with the louvered liner. The final phase was directed towards evaluating the advanced segmented liner and emissions at engine sea level takeoff pressure and temperature levels. In total, approximately 500 hours of sector rig operation were accumulated, and approximately 1000 performance/emissions data points were acquired.

4.1.1 Fuel Injector Characterization Program

Fuel injector cold flow testing was directed at quantitatively and qualitatively defining the aerodynamic performance of both the pilot and main zone fuel injectors. Various carburetor tube geometries were evaluated over a range of simulated combustor operating conditions to provide data for defining the initial sector rig injector configuration as well as a data base for modifications during the rig test. Testing was divided into three categories: (1) airflow calibrations and spray evaluations, (2) jet penetration and (3) two-dimensional flow visualization testing. Airflow and spray characterization tests of the pilot zone aerated fuel injectors were also conducted to support the sector rig test effort.

4.1.1.1 Airflow Calibration and Spray Characterization

Airflow calibrations of numerous carburetor tube geometries using 2X scale models (Figure 4.1.1-1) were performed to determine the effective airflow area (AC_d) and exit swirl strength. The test matrix, as presented in Table 4.1.1-I, included the effect of pressure drop, simulated fuel blockage and swirler blockage. Airflow calibrations of two candidate pilot zone fuel injectors were also conducted in the supporting test program.

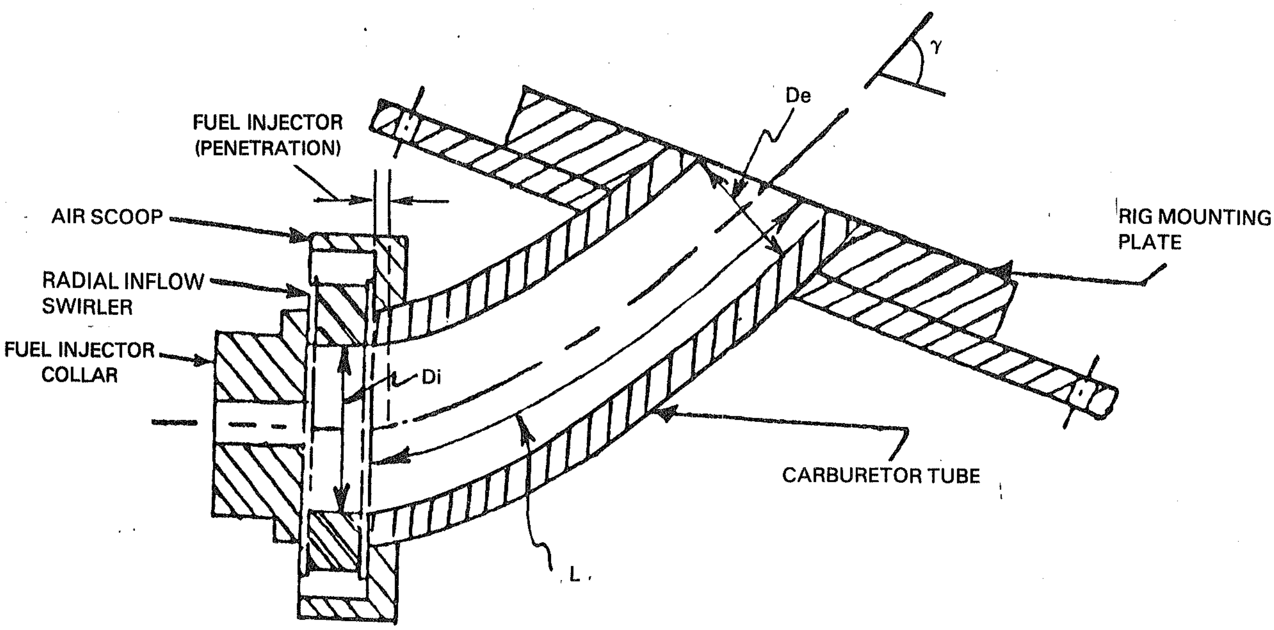


Figure 4.1.1-1 Typical 2X-Size Plexiglas Carburetor Tube Model Showing Geometric Variables

Carburetor tube spray characterization tests of two types were conducted. Initial tests with the 2X models evaluated the sensitivity of geometric variations to downstream fuel/ air spray quality over a range of air pressure drops of 1.5-2.5 percent and fuel flows of 10-13 kg/hr (24-30 lb/hr). The geometric variations, in addition to the five basic carburetor tube models, included: depth of fuel injector tip insertion, injector collar shape, radial inflow swirler size (partial blocking, extended length) and fuel injector spray geometry (conical flat spray). These tests in conjunction with the 2X model airflow calibration tests provided the data base for defining the initial sector rig carburetor tube design.

The second series of spray characterization tests measured fuel droplet size and distribution (Sauter Mean Diameter) downstream of the carburetor tube using a laser particle measurement system (Malvern Type ST 1800). Then tests were conducted using full size sector rig carburetor tube injectors (base and increased radial inflow swirler) over the test matrix defined in Table 4.1.1-II.

Similar spray characterization tests were conducted with the aerating pilot injectors to define the fuel Sauter Mean Diameter at simulated idle and sea level start conditions.

TABLE 4.1.1-I
AIRFLOW CALIBRATION MATRIX FOR
CARBURETOR TUBE MODELS

Run Number	Type	Purpose
1	o AC_d/Torque/Thrust vs $\Delta P/P$	o Baseline o Flow visualization
2	o AC_d with water injection vs $\Delta P/P$	o Determine effect of simulated fuel flow blockage on AC_d
3	o AC_d/Torque/Thrust vs $\Delta P/P$ o 25% blockage rings installed upstream or downstream	o Determine effect of swirler blockage rings on AC_d and swirl strength
4	o AC_d/Torque/Thrust vs $\Delta P/P$ o 50% blockage rings installed upstream or downstream	o Same as run number 3
5	o AC_d/Torque/Thrust vs $\Delta P/P$ o 30-deg blockage rings installed upstream or downstream	o Determine effect of inlet flow distortion on AC_d and swirl
6,7	o AC_d/Torque/Thrust vs $\Delta P/P$ o Diagnostic testing	o Evaluate candidate configurations for sector rig

TABLE 4.1.1-II

SPRAY CHARACTERIZATION MATRIX FOR CARBURETOR TUBES

Run	Conditions	Measuring Plane	Purpose
1	air = 148 kg/hr (328 lb/hr) fuel = 8 kg/hr (18 lb/hr)	Jet center line at 5.0 cm (2.0), 4.3 cm (1.7) and 3.5 cm (1.4 in) from eixt plane	Evaluate axial variation of fuel spray droplet Sauter mean diameter (SMD) at simulated SLTO conditions
2	air = 111 and 185 kg/hr (246 and 410 lb/hr) fuel = 8 kg/hr (18 lb/hr)	Jet centerline @ 3.5 cm (1.4 in) from exit plane	Evaluate effect of airflow velocity on SMD
3	air = 111 and 185 kg/hr (246 and 410 lb/hr) fuel = 3 kg/hr (7 lb/hr)	Jet centerline @ 3.5 cm (1.4 in) from exit plane	Evaluate effect of equivalence ratio and airflow on SMD
4	air = 65 and 108 kg/hr (144 and 240 lb/hr)	Jet centerline @ 3.5 cm (1.4 in) from exit plane	Evaluate SMD with core flow only (Secondary air passage blocked)
5	air = 99 and 166 kg/hr (220 and 367 lb/hr)	Jet centerline @ 3.5 cm (1.4 in) from exit plane	Evaluate effect of large height 1.80 cm (0.71 in) swirler on SMD

4.1.1.2 Jet Penetration Evaluations

Jet penetration tests were conducted to determine the interaction of simulated combustor flow with the swirling fuel/air mixture exiting from the carburetor tube injector using both scale models and sector rig carburetor tubes. The initial model test program also investigated penetration properties of "plain" dilution jets (flush hole) and "developed" jets (carburetor tube without swirlers) for comparison.

Fuel flow was simulated by using pressurized water containing dye to enhance flow visualization in these tests. To simulate the carburetor tube exit to main stream velocity ratio (U jet/U main) expected in the engine operating spectrum, carburetor tube exit to main stream velocity ratios ranging from 2 to 6.3 were tested. Hot wire anemometry was used to characterize the velocity field for selected configurations, with major emphasis on defining the jet centerline.

Jet penetration tests using actual sector rig carburetor tubes were conducted in a two-dimensional rig that simulated a three carburetor tube section of the combustor. Both single and three tube configurations were tested.

4.1.1.3 Flow Visualization

Flow visualization tests were performed with a two-dimensional Plexiglas® model of the diffuser/combustor section to evaluate shroud feed, combustor hood feed and pilot zone recirculation characteristics. Both dye and bubble injection were used for visual observation and photography with conventional lighting and a laser light source.

Flow visualization tests, using a sector rig carburetor tube injector that incorporated a Plexiglas® tube section, were also performed to determine the flow-field downstream of the radial airflow swirler.

4.1.2 Sector Combustor Rig Performance and Emissions Test Program

The principal purpose of this test series was to optimize air management and combustor fuel flow splits in terms of system aerothermal and emissions performance. These tests were conducted with the louvered liner combustor at the Energy Efficient Engine operating conditions consistent with the Environmental Protection Agency Parameter emissions requirements. These conditions are summarized in Table 4.1.2-I and the test program matrix is presented in Table 4.1.2-II.

The sequence of tests included a cold flow pressure loss evaluation, parametric testing at idle with only the pilot zone fuel injectors operative, definition of lean blowout characteristics, and pilot/main zone fuel split variations to assess emissions and exit gas temperature measurements. These tests, however, were preceded by calibrations and checks of functional equipment to ensure proper operation of facility equipment, instrumentation and data acquisition systems.

TABLE 4.1.2-I
SECTOR RIG TEST CONDITIONS

Condition	Compressor Exit Pressure MPa (psia)	Compressor Exit Temperature °C (°F)	Compressor Exit Flow kg/sec (lb/sec)	Fuel/Air Ratio
Idle	0.43 (63)	199 (391)	3 (7.5)	0.0098
Approach	1.16 (168)	348 (659)	7 (16.1)	0.0150
Climb	2.65 (384) 1.60 (232)*	501 (934)	14.9 (32.9) 9.0 (20)*	0.0230
Takeoff	3.06 (444) 1.63 (236)*	532 (991)	16.9 (37.3) 9.0 (20)*	0.0250

* Values indicate conditions for operating with louvered liner configurations

At each test condition, combustor operation was stabilized for approximately three minutes before data were acquired. Pressures and temperatures were obtained at each test condition, while emissions measurements were acquired at pre-selected conditions.

Tests for altitude stability and relight capability were conducted at simulated engine windmilling conditions. Actual Energy Efficient Engine combustor inlet temperature and pressure conditions were achieved, while fuel flow and airflow levels were scaled for the sector rig. The relight envelope for the Energy Efficient Engine, along with the range of conditions simulated, is identified in Figure 4.1.2-1. The range of engine equivalent fuel flows investigated was 21 to 283 kg/hr (48 to 624 lb/hr).

Altitude relight testing was conducted by setting the prescribed combustor inlet airflow, temperature, pressure and fuel flow, and by decreasing the pressure until the combustor would not light. Minimum pressure blowout tests were conducted by starting at a lighted condition and decreasing the pressure until blowout occurred. Sea level starting tests consisted of evaluating the elapsed time to light at various fuel flow rates.

4.1.3 Advanced Liner Evaluation Program

This final phase of the sector rig program was directed at determining liner wall temperatures and radial gradients, and demonstrating structural integrity of the advanced segmented liner in the full pressure and temperature environment of the Energy Efficient Engine. It also included assessing the effects of pressure on aerothermal and emissions performance as well as on the liner itself. Testing was conducted with inlet pressures up to 3.1 MPa (450 psia). In addition, liner wall temperatures were evaluated at inlet temperatures up to 576°C (1070°F).

Test conditions are summarized in Table 4.1.3-I. The program involved a cold flow pressure loss evaluation, plus tests to ascertain the impact on emissions and liner temperature with fuel/air and fuel flow split variations. A portion of the program also included testing with broad specification fuels.

SI Units

TABLE 4.1.2-II

SECTOR COMBUSTOR RIG PERFORMANCE AND EMISSIONS TEST MATRIX

Point	Condition	T_{t3} °C	P_{t3} MPa	W_{a3} kg/sec	Cust. Bleed kg/sec	Fuel Flow Pilot kg/sec	Fuel Flow Main kg/sec	Fuel Flow Total kg/sec	% Split Pilot/ Main	F/A (1) Burner	Smoke	Comments
120	CFPL	148	0.34	2.22								Cold Flow Pressure Loss
121				2.63								
122				1.37								
130		482	1.37	6.62								
131				7.84								
132				9.07								
20	Idle	199	0.43	3.42	0	0.024	0	0.024	100/0	0.0090		F/A variation
21						0.027		0.027		0.0098		
22						0.029		0.029		0.0108		
		190		3.46		0.027		0.027		0.0098		T_3 variation
		207		3.40		0.026		0.026		0.0098		
	Idle Inst	191	0.40	3.23	0.28	0.030	0	0.030	100/0	0.013		Customer bleed on
40	APP	348	1.15	7.30	0	0.088	0	0.088	100/0	0.0150		Fuel split variation
41						0.070	0.017	0.088	80/20		(6)	
42						0.053	0.035	0.088	60/40			
43						0.044	0.043	0.088	50/50			
44						(2)	(2)	0.082	(2)	0.0140		Fuel/Air variation at
45						(2)	(2)	0.094	(2)	0.0160		optimum split (2)
50	Climb	501	1.59 (5)	9 (5)	0	0.062	0.062	0.124	50/50	0.170	(6)	Fuel split variation
51						0.049	0.074	0.124	40/60		(6)	
52						0.037	0.087	0.124	30/70		(6)	
53						0.024	0.099	0.124	20/80		(6)	
54						(2)	(2)	0.131	(2)	0.018	(6)	Fuel air variation at
55						(2)	(2)	(3)	(2)	max (3)	(6)	optimum split (2)
60	SLTO	532	1.62 (5)	9 (5)	0	0.062	0.062	0.124	50/50	0.017		Fuel split variation
61						0.049	0.074	0.124	40/60		(6)	
62						0.037	0.087	0.124	30/70		(6)	
63						0.024	0.099	0.124	20/80			
64						(2)	(2)	0.131	(2)	0.018	(6)	Fuel air variation at
65						(2)	(2)	(3)	(2)	max (3)	(6)	optimum split (2)
70	Idle	199	0.43	3.42	0	0.027	0	0.027	100/0	0.0098		Repeat Idles
71		199	0.43	3.42	0	0.024	0	0.024	100/0	0.0090		
80	LBO	199	0.43	3.42	0	(4)	0	(4)	100/0			LBO at idle.
81		226	0.51	3.96	0	(4)	0	(4)	100/0			LBO at high idle.

(1) Burner fuel/air based on turbine cooling, Tangential On-Board Injection (TOBI) and sidewall flow percentage of 19.15%.
(2) Optimum fuel split to be determined during test and the corresponding pilot fuel flow (constant pilot fuel/air) maintained during fuel/air variation.
(3) Do not exceed 1537°C (2800°F) on any Station 4 gas turbine couple or 954°C (1750°F) on any vane skin turbine couple.
(4) Record fuel flow at lean stability limit.
(5) Reduced (simulated) conditions
(6) Smoke measurements to be made.

NOTE: Purge vanes during light off and LBO and during period when emissions are not being recorded.

TABLE 4.1.2-II

SECTOR COMBUSTOR RIG PERFORMANCE AND EMISSIONS TEST MATRIX

Point	Condition	T_{t3} °F	P_{t3} psia	W_{a3} lb/sec	Cust. Bleed lb/sec	Fuel Flow Pilot lb/sec	Fuel Flow Main lb/sec	Fuel Flow Total lb/sec	% Split Pilot/ Main	F/A (1) Burner	Smoke	Comments
120	CFPL	300	50	4.90								Cold Flow Pressure Loss
121				5.80								
122				6.70								
130		900	200	14.60								
131				17.30								
132				20.00								
20	Idle	391	63	7.55	0	0.055	0	0.055	100/0	0.0090		F/A variation
21						0.060		0.060		0.0098		
22						0.066		0.066		0.0108		
		375		7.63		0.061		0.061		0.0098		T_3 variation
		405		7.50		0.059		0.059		0.0098		
	Idle Inst	377	59	7.13	0.62	0.067	0	0.067	100/0	0.013		Customer bleed on
40	APP	659	168	16.1)	0	0.195	0	0.195	100/0	0.0150		Fuel split variation
41						0.156	0.039	0.195	80/20		(6)	
42						0.117	0.078	0.195	60/40			
43						0.098	0.097	0.195	50/50			
44						(2)	(2)	0.182	(2)	0.0140		Fuel/Air variation at
45						(2)	(2)	0.208	(2)	0.0160		optimum split (2)
50	Climb	934	232 (5)	20 (5)	0	0.137	0.138	0.275	50/50	0.170	(6)	Fuel split variation
51						0.110	0.165	0.275	40/60		(6)	
52						0.082	0.193	0.275	30/70		(6)	
53						0.055	0.220	0.275	20/80		(6)	
54						(2)	(2)	0.291	(2)	0.018	(6)	Fuel air variation at
55						(2)	(2)	(3)	(2)	max (3)	(6)	optimum split (2)
60	SLTO	991	236 (5)	20 (5)	0	0.137	0.138	0.275	50/50	0.017		Fuel split variation
61						0.110	0.165	0.275	40/60		(6)	
62						0.082	0.193	0.275	30/70		(6)	
63						0.055	0.220	0.275	20/80			
64						(2)	(2)	0.291	(2)	0.018	(6)	Fuel air variation at
65						(2)	(2)	(3)	(2)	max (3)	(6)	optimum split (2)
70	Idle	391	63	7.55	0	0.060	0	0.060	100/0	0.0098		Repeat Idles
71		391	63	7.55	0	0.055	0	0.055	100/0	0.0090		
80	LBO	391	63	7.55	0	(4)	0	(4)	100/0			LBO at idle.
81		440	75	8.75	0	(4)	0	(4)	100/0			LBO at high idle.

(1) Burner fuel/air based on turbine cooling, Tangential On-Board Injection (TOBI) and sidewall flow percentage of 19.15%.
(2) Optimum fuel split to be determined during test and the corresponding pilot fuel flow (constant pilot fuel/air) maintained during fuel/air variation.
(3) Do not exceed 1537°C (2800°F) on any Station 4 gas turbine couple or 954°C (1750°F) on any vane skin turbine couple.
(4) Record fuel flow at lean stability limit.
(5) Reduced (simulated) conditions
(6) Smoke measurements to be made.

NOTE: Purge vanes during light off and LBO and during period when emissions are not being recorded.

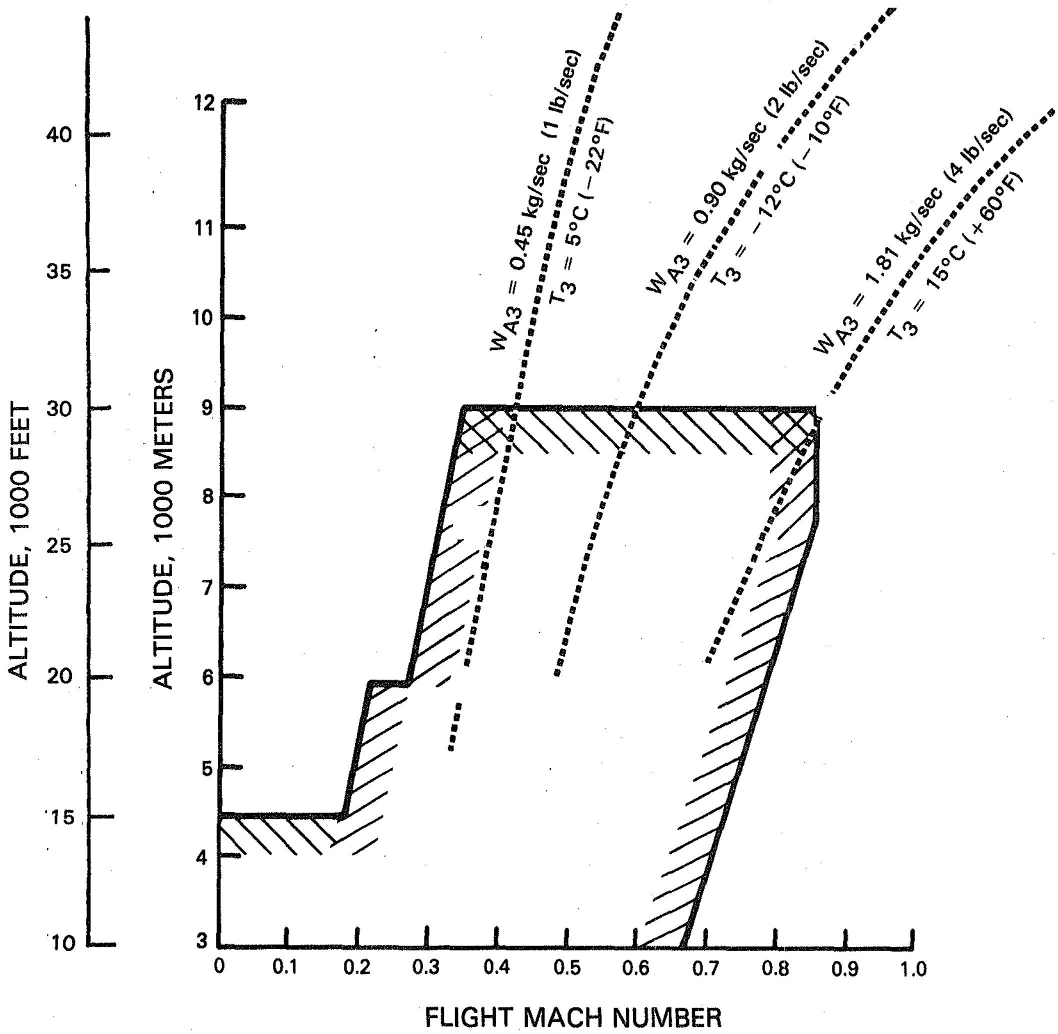


Figure 4.1.2-1 Energy Efficient Engine Relight Envelope

4.2 TEST FACILITIES

4.2.1 Facilities for Fuel Injector Characterization Program

Four low-pressure facilities were utilized to test the large scale plexiglas carburetor tube models and full size sector rig hardware evaluations during the fuel injector characterization program. The test stands included X-415, X-408, X-173, and X-420, all of which are located at the Pratt & Whitney Aircraft Commercial Products Division in East Hartford, Connecticut. In addition, fuel droplet size evaluations were performed at the United Technologies Research Center. Independent evaluations of base design pilot fuel injectors were also conducted by the vendors to confirm performance characteristics.

SI Units

TABLE 4.1.3-I

ADVANCED LINER EVALUATION PROGRAM

Point	Condition	T_{t3} °C	P_{t3} MPa	W_{a3} kg/sec	Cust. Bleed kg/sec	Fuel Flow Pilot kg/sec	Fuel Flow Main kg/sec	Fuel Flow Total kg/sec	% Split Pilot/Main	F/A (1) Burner	Smoke	Comments
	GFPL					0	0	0		0		
120	CFPL	510	2.07	11.2								Cold Flow Pressure Loss
121				11.6								
122				12.0								
130		204	0.69	4.7								
131				4.9								
132				5.1								
80	LBO	199	0.43	3.42	0	(4)	0	(4)	100/0			LBO at idle
20	Idle	199	0.43	3.42	0	0.024	0	0.024	100/0	0.0090		
21						0.027		0.027		0.0098		
22						0.030		0.030		0.0110		
40	APP	348	1.16	7.3	0	0.088	0	0.088	100/0	0.015		Fuel split variation
41						0.076	0.012	0.088	86/14	0.015		
42						0.082	0.012	0.094	87/13	0.016		
43						0.070	0.012	0.082	85/15	0.014		
44						0.076	0.006	0.082	92/8	0.014		
45						0.076	0.017	0.094	81/19	0.016		
50	Climb	501	1.60	9	0	0.039	0.092	0.131	30/70	0.018		Fuel split variation
51						0.024	0.102	0.131	22/78	0.018		
52					0.05		0.112	0.131	15/85	0.018		
53						(2)	(2)	0.146	(2)	0.020		Fuel air variation at optimum split (2).
54								0.154		0.021		
55								0.161		0.022		
56								(3)		max (3)		
950	Climb	501	2.65	14.9(5)	0	0.065	0.151	0.217	30/70	0.018		
951						0.048	0.169	0.217	22/78	0.018		
952						0.032	0.184	0.217	15/85	0.018		
953						(2)	(2)	(3)	(2)	max (3)	(6)	Smoke at max f/a.
960	SLTO	532	3.06	16.9(5)	0	(2)	(2)	0.246	(2)	0.018	(6)	Fuel air variation at optimum split.
961								0.273		0.020		
962								0.300		0.022		
963								0.314		0.023 (3)	(6)	Smoke at max f/a and backtrack if value
964								0.328		0.024 (3)	(6)	is high
965								0.342		0.025 (3)		

(1) Burner fuel/air based on turbine cooling, Tangential On-Board Injection (TOBI) and sidewall flow percentage of 19.15%.
(2) Optimum fuel split to be determined during test and the corresponding pilot fuel flow (constant pilot fuel/air) maintained during fuel/air variation.
(3) Do not exceed 1537°C (2800°F) on any Station 4 gas turbine couple or 954°C (1750°F) on any vane skin turbine couple.
(4) Record fuel flow at lean stability limit.
(5) Full conditions
(6) Smoke measurements to be made.

NOTE: Purge vanes during light off and LBO and during period when emissions are not being recorded.

TABLE 4.1.3-I

ADVANCED LINER EVALUATION PROGRAM

Point	Condition	T_{t3} °F	P_{t3} psia	W_{a3} lb/sec	Cust. Bleed lb/sec	Fuel Flow Pilot lb/sec	Fuel Flow Main lb/sec	Fuel Flow Total lb/sec	% Split Pilot/Main	F/A (1) Burner	Smoke	Comments
	GFPL					0	0	0		0		
120	CFPL	950	300	24.8								Cold Flow Pressure Loss
121				25.6								
122				26.6								
130		400	100	10.5								
131				10.9								
132				11.4								
80	LBO	391	63	7.55	0	(4)	0	(4)	100/0			LBO at idle
20	Idle	391	63	7.55	0	0.055	0	0.055	100/0	0.0090		
21						0.060		0.060		0.0098		
22						0.067		0.067		0.0110		
40	APP	659	168	16.1	0	0.195	0	0.195	100/0	0.015		Fuel split variation
41						0.168	0.027	0.195	86/14	0.015		
42						0.181	0.027	0.208	87/13	0.016		
43						0.155	0.027	0.182	85/15	0.014		
44						0.168	0.014	0.182	92/8	0.014		
45						0.169	0.039	0.208	81/19	0.016		
50	Climb	934	232	20	0	0.087	0.204	0.291	30/70	0.018		Fuel split variation
51						0.064	0.227	0.291	22/78	0.018		
52					0.12		0.247	0.291	15/85	0.018		
53						(2)	(2)	0.323	(2)	0.020		Fuel air variation at optimum split (2).
54								0.340		0.021		
55								0.356		0.022		
56								(3)		max (3)		
950	Climb	934	384 (5)	32.9 (5)	0	0.144	0.335	0.479	30/70	0.018		
951						0.106	0.373	0.479	22/78	0.018		
952						0.072	0.407	0.479	15/85	0.018		
953						(2)	(2)	(3)	(2)	max (3)	(6)	Smoke at max f/a.
960	SLTO	991	444 (5)	37.3 (5)	0	(2)	(2)	0.543	(2)	0.018	(6)	Fuel air variation at optimum split.
961								0.603		0.020		
962								0.663		0.022		
963								0.694		0.023 (3)	(6)	Smoke at max f/a and backtrack if value
964								0.724		0.024 (3)	(6)	is high
965								0.754		0.025 (3)		

(1) Burner fuel/air based on turbine cooling, Tangential On-Board Injection (TOBI) and sidewall flow percentage of 19.15%.
(2) Optimum fuel split to be determined during test and the corresponding pilot fuel flow (constant pilot fuel/air) maintained during fuel/air variation.
(3) Do not exceed 1537°C (2800°F) on any Station 4 gas turbine couple or 954°C (1750°F) on any vane skin turbine couple.
(4) Record fuel flow at lean stability limit.
(5) Full conditions
(6) Smoke measurements to be made.

NOTE: Purge vanes during light off and LBO and during period when emissions are not being recorded.

Test stand X-415 was used to conduct airflow calibrations. This is an airflow facility used specifically with an existing rig to evaluate the airflow characteristics of conventional fuel injector/swirler assemblies. Air is delivered to the stand at flow rates up to 0.6 kg/sec (1.5 lb/sec) at a pressure of 0.69 MPa (100 psig). A regulator decreases the rig inlet pressure to slightly above atmospheric ($\sim$0.11 MPa ($\sim$16 psia)) level. A flat plate orifice and a series of flow straighteners comprise the remainder of the inlet system. Thrust and torque measuring equipment at the exit of the test piece are used to determine the flow swirl strength.

A portion of the spray characterization tests was conducted in stand X-408. This facility consists of a pressure chamber that houses the carburetor tube plenum chamber. The tank is pressurized to a predefined level by a 13.8 MPa (2000 psi) nitrogen gas supply. Plenum chamber and fuel tank pressures are regulated separately. Jet-A fuel is then supplied to the test injector, with the flow rates measured by turbine flow meters. Three windows, installed 90-degrees apart on the pressure vessel, permit observing and photographing sprays while the test is in progress.

Quantitative droplet size characterization tests were conducted at the United Technologies Research Center's Ambient Fuel Spray Facility. In this facility, a cold start temperature of -23°C (-10°F) can be attained using an existing fuel conditioning system. Droplet distribution data and Sauter Mean Diameter measurements are obtained using a Malvern ST-1800 Particle Size/Distribution Analyzer. Photographic records of the spray characteristics are acquired using a conventional flood-lite television system and a strobe illuminated Instar 1120 television system. From visual measurements and the image displayed on a conventional video monitor, the mean spray angle can be measured. The Instar system uses a 10-microsecond high intensity strobe to illuminate the spray pattern and produces 120 optically clear pictures per second. The strobe illumination is capable of stopping the motion of much of the spray and from these pictures variations in spray angle and quality can be evaluated.

Test stand X-173 was used for the jet penetration test program. This facility is used for development testing of diffusers and studies of mixing and diffusion. In this facility, air is delivered to the rig at flow rates up to 762 kg/sec (1682 lb/sec) at 0.027 MPa (4 psig). A secondary air supply system is also available at airflow rates up to 0.6 kg/sec (1.5 lb/sec) at 0.69 MPa (100 psig). Inlet ducting is equipped with a 60 cm (24 in) control valve and a flat plate orifice for airflow measurement. For this effort, a Plexiglas® rig (Figure 4.2.1-1) was designed with provisions for static and total pressure instrumentation, along with a splash plate and screen to ensure uniform air feed characteristics.

A water tunnel facility, stand X-420, was used to observe system flow characteristics with a full-scale, two-dimensional, 45-degree (three nozzle) sector model of the diffuser/combustor section. Figure 4.2.1-2 shows a schematic of the test setup. As indicated, the facility uses injected dye and a bubble generator to enable observation of flow characteristics both within and external to the combustor liners. Also, the water tunnel has photographic equipment with conventional lighting and a laser light source to acquire data.

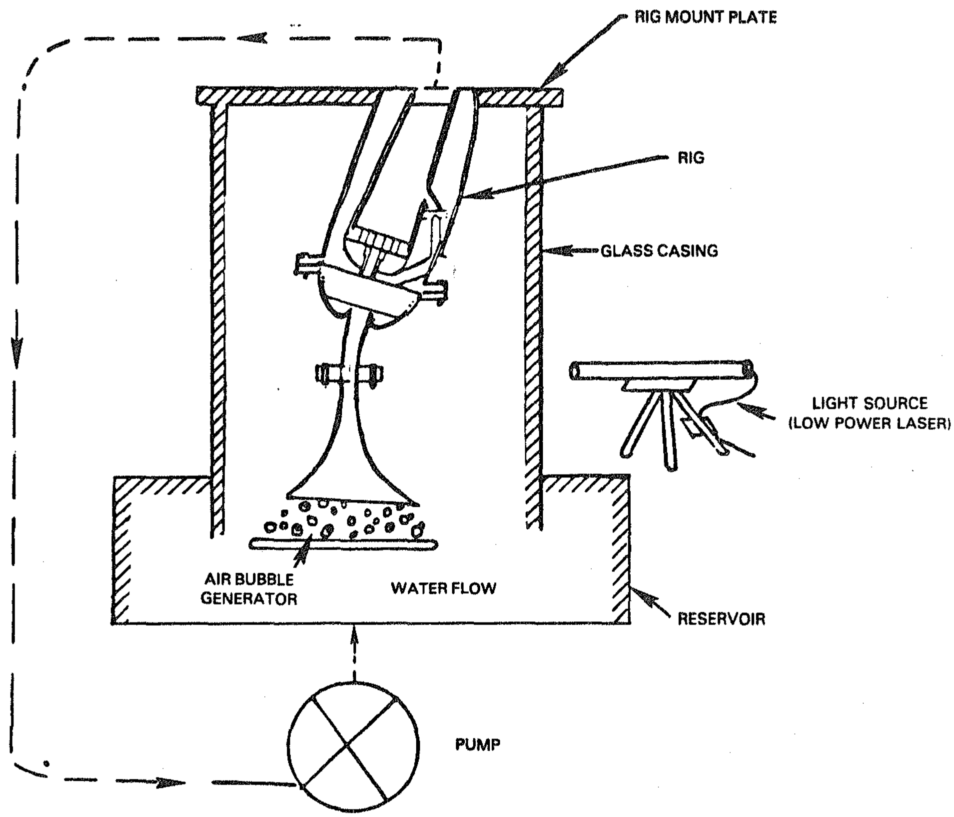


Figure 4.2.1-1 Schematic of Jet Penetration Rig

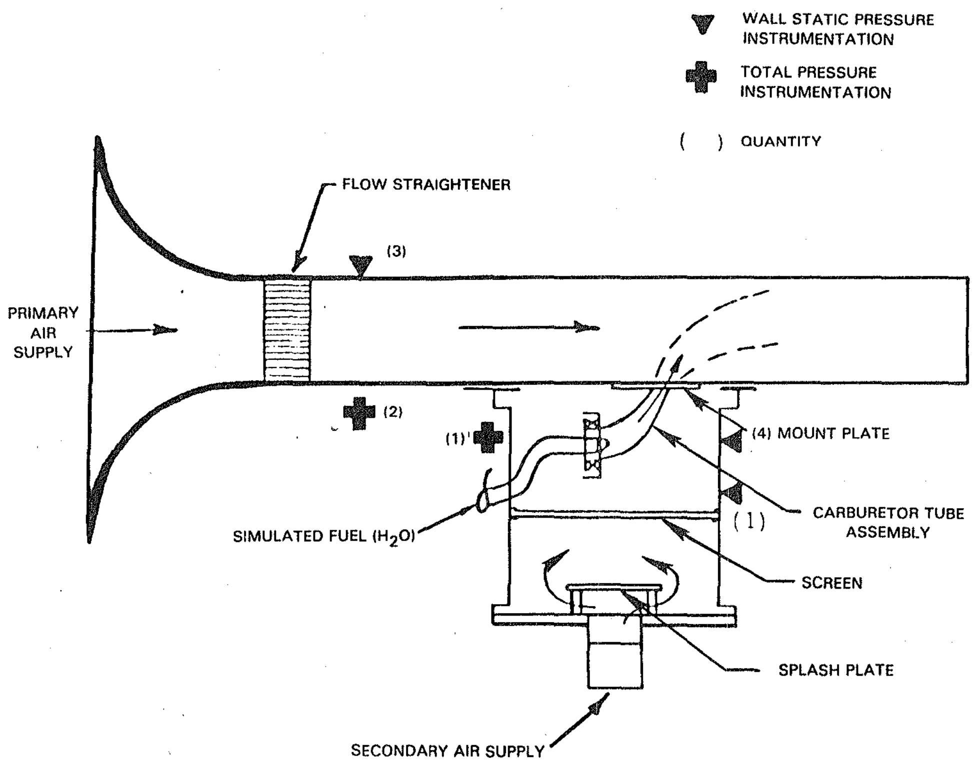


Figure 4.2.1-2 Schematic of Two-Dimensional Water Tunnel Rig

4.2.2 Sector Rig Test Facilities

Three test facilities were required to complete the sector combustor rig test program. These included stand X-903 for performance and emissions evaluations with the louvered liner test rig, stand X-960 which was the source of high pressure air supplied to stand X-903 for the segmented liner tests, and stand X-306 for altitude relight evaluations. A description of these facilities is presented in the following paragraphs.

4.2.2.1 Sector Rig Test Facility (Stand X-903)

The X-903 test facility is one of the five pressurized combustor development stands located in the Middletown Test Facility complex at the Pratt & Whitney Aircraft Middletown, Connecticut plant.

Normally, nonvitiated inlet air at temperatures up to 648°C (1200°F) is supplied by a gaseous/liquid fuel-fired heat exchanger. Airflow up to 11 kg/sec (25 lb/sec) and up to 4.31 MPa (625 psia) is provided by two steam-driven, two-stage turbocompressors and one six-stage, steam-driven boost compressor. The main facility fuel boost pumps supply fuel at pressures up to 10.34 MPa (1500 psia) and flow rates up to 0.6 kg/sec (1.5 lb/sec). Fuel flow measurements are obtained by using multiple turbine flowmeters, in series, in each fuel line.

Secondary services include high-pressure cooling water, steam and air, various electrical power supplies, and inert gas purge systems. Exhaust gases are collected in a water-cooled exhaust duct and then ducted underground to an expansion and liquid separation pit at the base of the main exhaust stack.

The combustor test rig is mounted within a cylindrical pressure tank. Tank pressurization is automatically controlled to 0.04 MPa (6 psi) above rig pressure. In this manner, the pressure load is supported by the facility pressure vessel, permitting experimental hardware to be of relatively lightweight construction. The thermal load is carried by the test rig. The main tank is cooled with an amount of purge air equal to 5 to 10 percent of combustor inlet airflow. A retractable tank section with a quick-disconnect breechlock seal is provided to enable easy access to the test rig.

Three systems are available for data processing. The first is especially helpful in troubleshooting during the test and consists of two Texas Instruments four-pen recorders that monitor the output of the instruments and provide a continuous real time record for either immediate inspection or subsequent analysis. The second system, a Tektronix digital magnetic tape cartridge recorder, records data on command for storage and possible later processing on an IBM 370 computer. The third is an on-line Univac that provides essentially real time data recording and analysis. Raw data are transmitted in terms of digital counts from the test facility to the computer center via a telephone link. The computer reduces the data, converts it to engineering units and displays the results on a display scope at the test facility. Data can then be reviewed, after which printed output can be obtained at either the test location or at the computing center. The printed output includes raw and reduced data for both performance and gas analysis evaluation.

The test stand has separate and permanently installed emissions and smoke measurement systems that are available to support the test effort. The emissions instrumentation and sample-handling system were designed in compliance with specifications of the Society of Automotive Engineer Aerospace Recommended Practice ARP-1256 and Environmental Protection Agency 40CFR87. Gas analysis instruments for the measurement of the following products of combustion are available:

- Carbon dioxide and carbon monoxide are measured with a non-dispersive infrared (NDIR) instrument (Beckman Model 865).

- Total unburned hydrocarbons are measured with a Beckman Model 402 heated flame ionization detector.

- Nitric oxide and total oxides of nitrogen are measured with a TECO Model 14D Chemiluminescence analyzer.

- Oxygen is measured with a Scott Model 250 Paramagnetic O_2 analyzer.

The combustor rig exhaust gas sample is distributed to the various instruments, with each instrument having its own flow metering system. Steam trace lines are used to maintain gas sample temperature levels in compliance with Society of Automotive Engineer (SAE) Specification ARP-1256 and Environmental Protection Agency 40CFR87. The sample handling is shown schematically in Figure 4.2.2-1.

A complete set of standard gases is available. These gases are traceable to the National Bureau of Standards through a set of standard reference material (SRM) gases, as shown by the flow diagram in Figure 4.2.2-2.

Combustor exhaust smoke measurements are obtained through a smoke measuring system that conforms to specifications of the Society of Automotive Engineers Aerospace Recommended Practice, ARP-1179. The Environmental Protection Agency exhaust smoke measurement system is defined in 40CFR87. It is based upon and virtually identical to the Society of Automotive Engineer system. The smoke measuring system (smoke meter) is a semiautomatic electro-mechanical device that incorporates many features to permit recording smoke data with precision and relative ease of operation.

The system is designed to minimize variability from differences in operating techniques. One of these features is a volume-controlled, solenoid-activated main sampling valve having "closed", "sample" and "bypass" positions. This configuration permits precise control of the sample size over relatively short sample times.

The smoke measuring system also includes a bypass loop around a positive displacement volume measurement meter to ensure that the meter is in the circuit only during a sample collection and leak check modes. Other design features include automatic temperature control for the sample line and filter holder and silicon rubber filter holders with support screens for ease of filter handling.

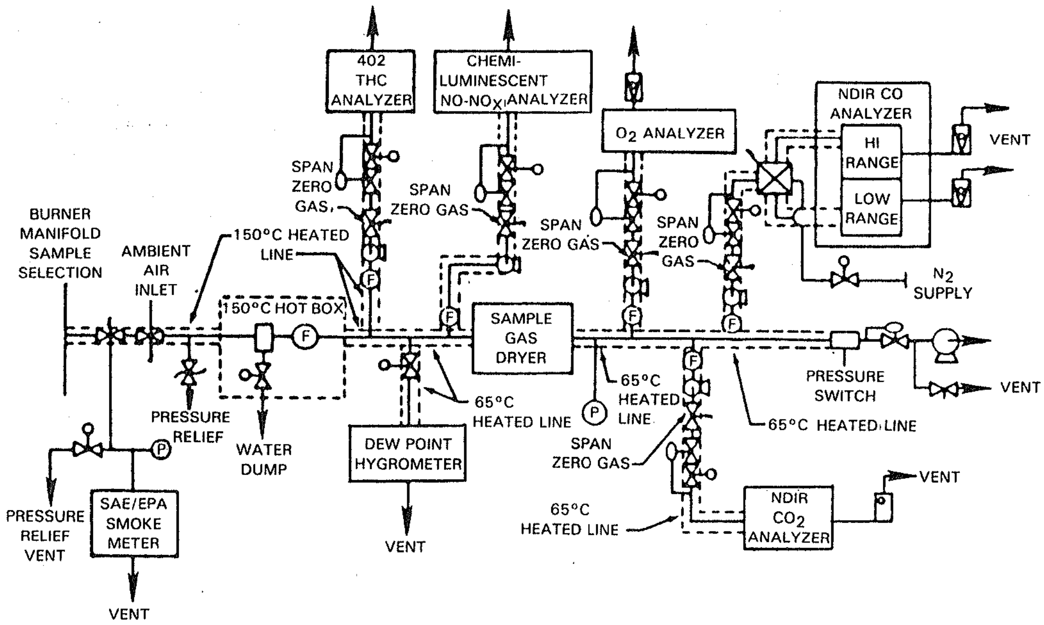


Figure 4.2.2-1 Gas Emissions Measuring System

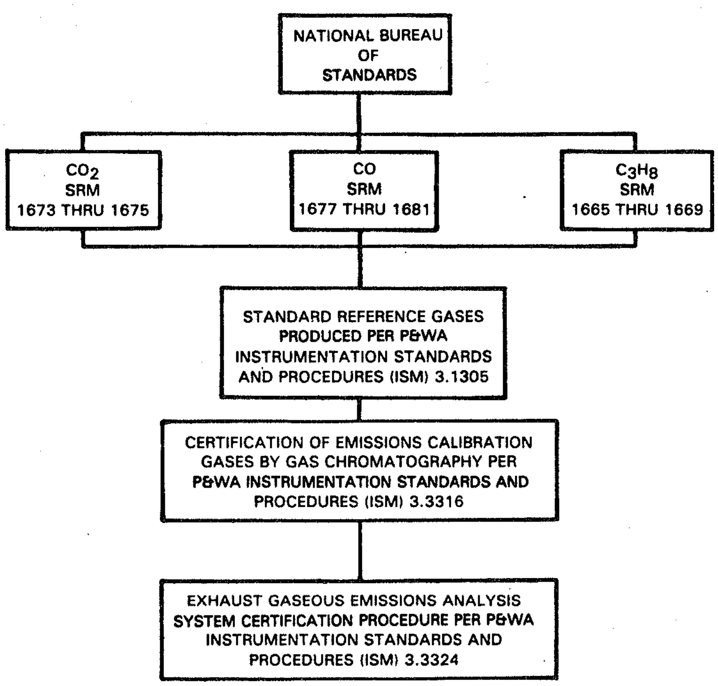


Figure 4.2.2.-2 Flow Diagram Identifying Method for Tracing Gases to National Bureau of Standard Through Standard Reference Material Gases

4.2.2.2 High-Pressure Combustion Test Facility (Stand X-960)

The High Pressure Combustion Laboratory (Stand X-960) is a new annular combustor test facility located at the Pratt & Whitney Aircraft Middletown Complex. This facility has the capability for testing systems up to 1.94 m (6 ft) in diameter (such as JT9D engine series combustors) with a maximum discharge temperature of 1815°C (3300°F). A schematic of the test facility is shown in Figure 4.2.2-3, and Table 4.2.2-I shows the test capabilities. The air supply of this facility was provided to stand X-903 to conduct the tests with the advanced segmented liner.

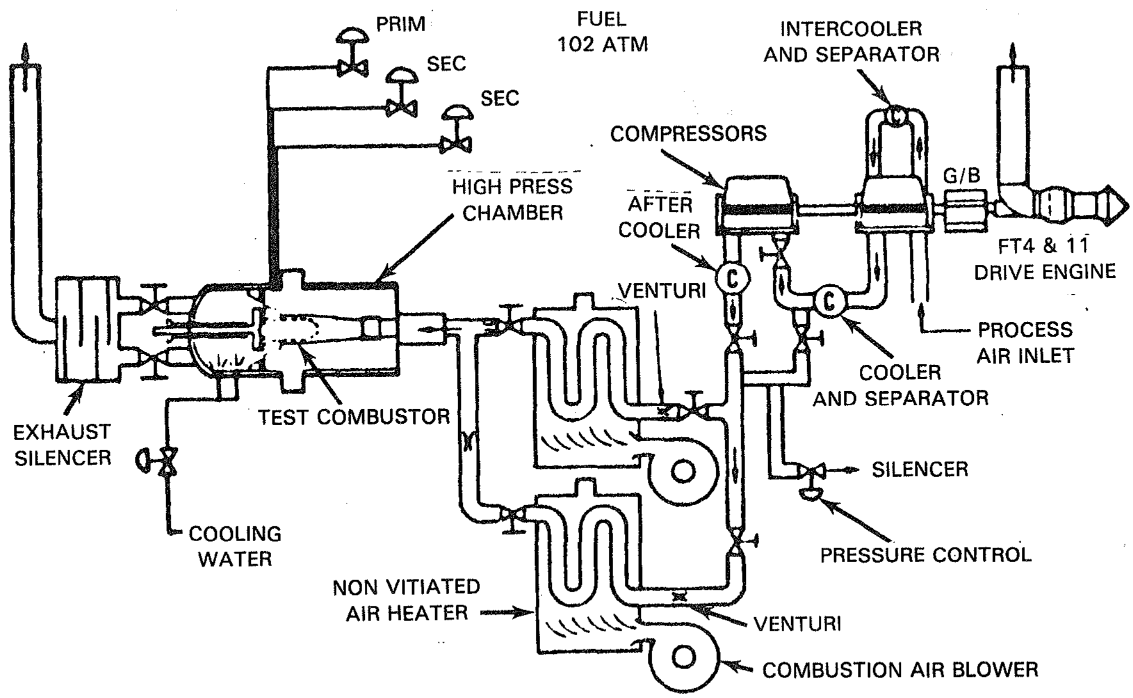


Figure 4.2.2-3 Stand X-960 High-Pressure Combustor Research Facility

4.2.2.3 Altitude Relight Facility (Stand X-306)

The altitude relight facility is a multiduct, subatmospheric test facility designed to test combustors at either sea level or altitude conditions. It allows testing under windmilling conditions encountered in actual flight. This facility has been used extensively for altitude relight and stability programs with virtually all Pratt & Whitney Aircraft engines. Exhaustor capability as low as 6,894 Pa (1 psi) is provided by five 335 kw (450 hp) Ingersol-Rand vacuum pumps rated at 3,657 m^3/min (12,000 ft^3/min) free air discharge.
The stand refrigeration equipment provides the capability of cooling 4 kg/sec (10 lb/sec) of dried air to -47°C (-54°F).

TABLE 4.2.2-I
TEST STAND X-960 CAPABILITIES

Process Air System

Rated airflow - 45 kg/sec (100 lb/sec) at 4.48 MPa (650 psia)
Inlet temperature - 85°C (185°F) to 648°C (1200°F)

Supplementary Air System

11 kg/sec (25 lb/sec) at 4.48 MPa (650 psia)

Fuel System

166 lit/min (44 gal/min) at 10.34 MPa (1500 psia) - Jet-A or special fuels

Chamber Capabilities

Chamber inner diameter - 1.94 m (6 ft)
Rig discharge temperature - 1815°C (3300°F)

Data Acquisition and Reduction Systems

Steady state - 1600 channels (temperatures, pressures, flows)
Emissions measuring instrumentation - meets federal Environmental Protection Agency (EPA) requirements
Data reduction - on-line Univac computer

4.3 TEST INSTRUMENTATION

The sector rig test configurations had a variety of instrumentation to monitor and record operating conditions as well as performance and emissions. The instrumentation, including the type of sensor, quantity and location, was determined on the basis of analyses and Pratt & Whitney Aircraft's experience in developing advanced combustion systems. Table 4.3-I lists the instrumentation used in the sector rig test program.

4.3.1 Exit Instrumentation

Both traversing and stationary exit instrumentation were available. The instrumentation measured exit pressure and temperature conditions and acquired gas samples for emissions analysis.

The traversing instrumentation rake, as shown in Figure 4.3.1-1, is a multi-probe design consisting of five radial gas sampling elements and five total temperature sensing elements, spanning a radial distance of 5.79 cm (2.28 in). The probe tips are accurately spaced to provide equal area averaging for each sensor. This is accomplished by decreasing the spacing between adjacent sensors (moving radially outward) so that each of the five sensors sweeps an annular area of equal magnitude.

TABLE 4.3-I
SECTOR RIG TEST INSTRUMENTATION

Location	Measurement/Type	Quantity	Purpose
Inlet	o 4-element total pressure probes o 4-element total temperature probes o inner/outer wall static pressure taps	6 5 5/5	o Rig Inlet Total pressure and temperature profiles
Prediffuser	o inner wall static pressure taps (2 rows) o outer wall static pressure taps (2 rows)	6 6	o Prediffuser performance
Diffuser Case Struts	o 5-leading edge total pressure	4 struts	o Prediffuser exit profile
Outer Shroud	o 3 rows-wall static pressure taps o 2 rows-kiel head total pressure o hydrocarbon sniffer	6 each row 2 each row 1	o Liner feed pressure map o Safety
Inner Shroud	o 2 rows-wall static pressure taps o 2 rows-kiel head total pressure o hydrocarbon sniffer	6 each row 2 each row 1	o Liner feed pressure map o Safety
Combustor Hood	o Kiel head total pressure o static pressure taps	2 2	o Bulkhead feed pressure
Inner liner	o Thermocouples o Wall static pressure taps o Low profile static pressure taps	10(louver) 16(segment) 2 2	o Liner temperature o Combustor pressure o Shroud pressure
Outer liner	o Thermocouples o Wall static pressure taps o Low profile static pressure taps	13(louver) 20(segment) 5 4	o Liner temperature o Combustor pressure o Shroud pressure
Exit	o Vane pack 5 leading edge thermocouples 4 leading edge gas sampling ports 5 P_T ports	 8 vanes 8 vanes 4 vanes	 o Exit total temperature profiles o Emissions/smoke o Exit total pressure
	o Traversing Pack 5 leading edge thermocouples 5 leading edge gas sampling ports	1	o Exit total temperature profiles o Emission/smoke/exit total pressure

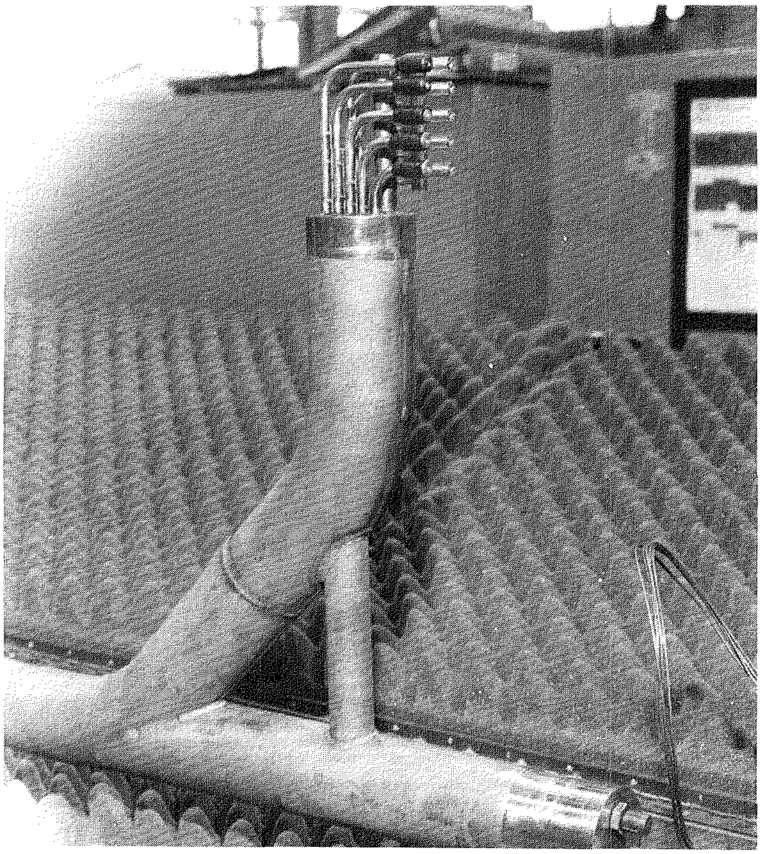


Figure 4.3.1-1 Traversing Instrumentation Rake Prior to Rig Assembly

The emissions probes are air cooled, and the port is designed with a venturi section at the inlet to ensure equal sampling flows from each element. The venturi throat is 0.116 cm (0.046 in) diameter, which then diverges to match the diameter of the Hastelloy X material sampling tube. To provide the proper (SAE ARP-1256) temperature quenching environment for the exhaust emissions samples, the emissions tubes are insulated and cooled with 176°C (350°F) steam.

Total temperature is recorded with thermocouples by semistaging the impact gas stream with a shield over the couple and controlling the overboard bleed rate to ensure good convective heat transfer from the gas to the sensor. A second shield encompasses the first to serve as a cooling shield for the entire probe tip when data are not being acquired. Cooling air is directed to each probe tip from a separate supply line with the flow rate regulated from the control room. Similarly, air is used to cool the sensor when data are not being acquired to increase instrumentation life. The thermocouples are made of platinum and platinum plus 20 percent Rhodium alloy, and encased in a platinum plus 20 percent Rhodium sheath insulated with magnesium oxide. To prevent corrosion, the thermocouple leads to the probe are passed through an insulating tube.

The stationary exit instrumentation consists of eight emissions/temperature vanes equally distributed about the exit arc-annulus centerline, two pressure probe vanes on the end of each emissions vane pack, and one dummy vane at each outboard end of the pressure vane sections. Because of side wall effects, the exit data acquired at the outboard ends of the rig are not used. As a result, the dummy vanes are installed since there is no requirement for instrumentation at these locations.

Figure 4.3.1-2 (a) shows the designs of the three different vanes. All vanes are flat with parallel sides and an outside width dimension of 0.952 cm (0.375 in). The vane leading edge is constructed of a 0.952-cm (0.375-in) tube that connects to a manifold on the opposite side. The manifold covers the remaining cross-sectional area of the vane. The vanes are air cooled. Film cooling holes (0.063 cm (0.025 in) in diameter) are located in a 0.381 cm (0.150 in) staggered array. The holes are canted on the sides 30 degrees to downstream. This allows the introduction of cooling air to the leading edge tube and the used coolant can be captured for film cooling the remaining vane surfaces, thereby conserving the limited total air supply to the rig.

The stationary exit emissions/temperature instrumentation consists of five thermocouples, spanning a radial distance of 5.79 cm (2.28 in), and four emissions sampling ports equally spaced between the thermocouples, as shown in Figure 4.3.1-2 (b). The probes are constructed in venturi sections, but throat diameters are smaller 0.063 cm (0.025 in) than in the traversing rake because of manifolding considerations as well as a requirement to limit the lead-in line total flow rate. In addition, it was necessary to manifold the emissions heads in groups of four as a result of the limited number of steam-heated lines installed from the rig to the control room.

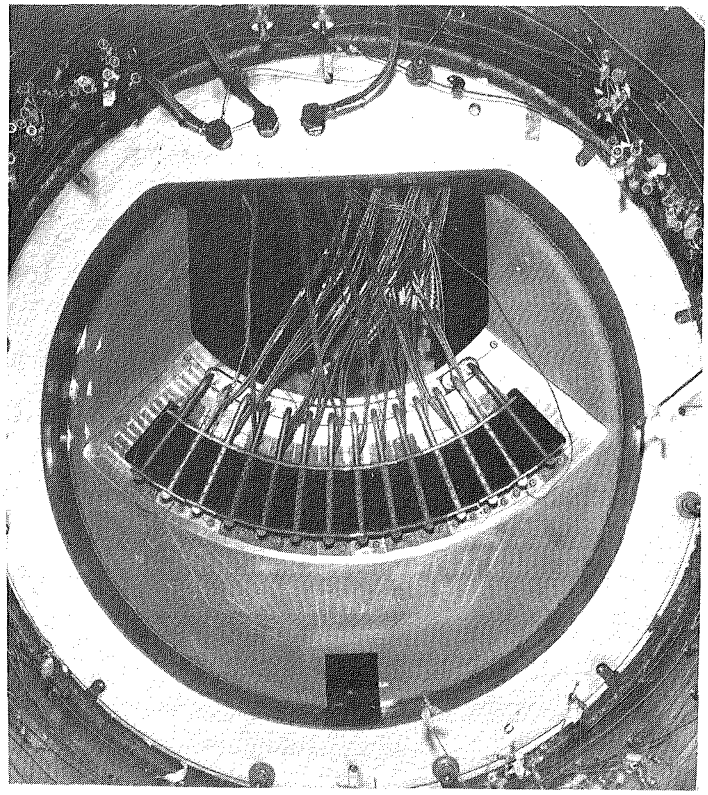
The emissions probes are air cooled. To provide the proper temperature (SAE ARP-1256) quenching environment for the exhaust emissions samples, the emissions tubes are insulated and cooled with 176°C (350°F) steam.

Total temperature is recorded with thermocouples in the same manner as with the traversing rake. Thermocouples are constructed of the same material as those on the traversing rake.

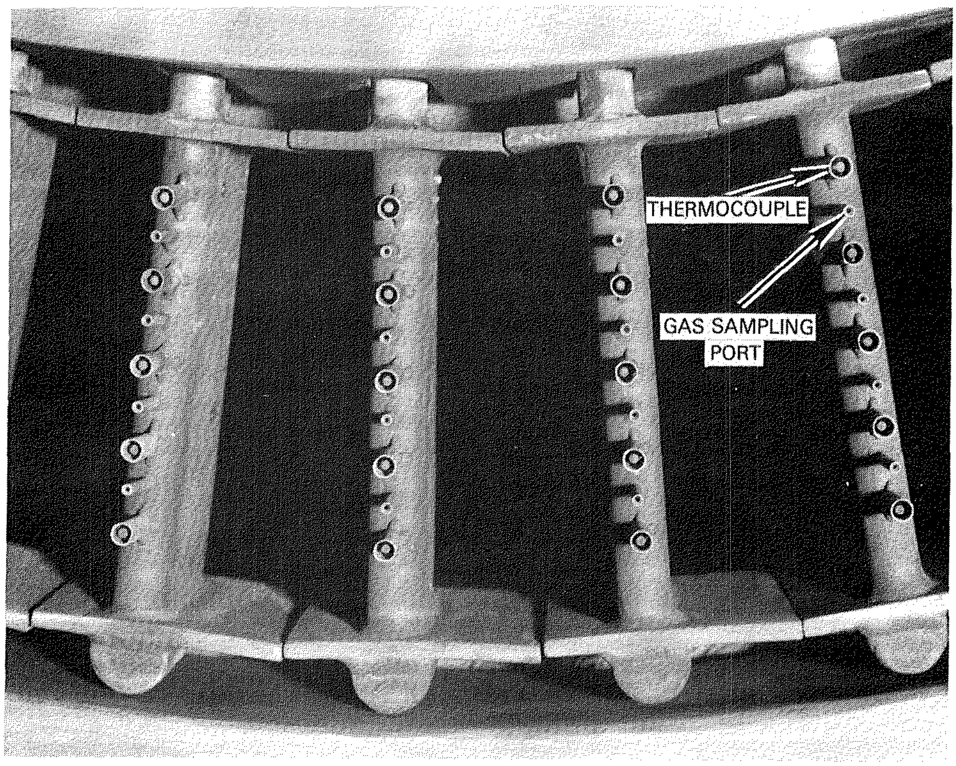
4.3.2 Liner Temperature Instrumentation

Both the louvered and segmented liners were instrumented with thermocouples to measure metal surface temperatures and detect hot spots. In the louvered liner rig, a total of 23 thermocouples was installed on the shroud side of the inner and outer liner. These were primarily used to ensure safe operation of the combustor.

The segmented liner, in contrast, was instrumented with imbedded thermocouples to monitor overall liner thermal-mechanical performance. A total of 36 hot side thermocouples was used at the locations shown in Figure 4.3.2-1. Four additional thermocouples were provided to measure temperatures in the hook attachment area. Thermal sensitive paint was also used on liner panels to show hot side temperatures and thermal gradients.



(a) INSTRUMENTED VANE PACK



(b) CLOSE-UP VIEW OF VANE INSTRUMENTATION

Figure 4.3.1-2 Stationary Exit Instrumentation (Vane Pack) Looking Downstream

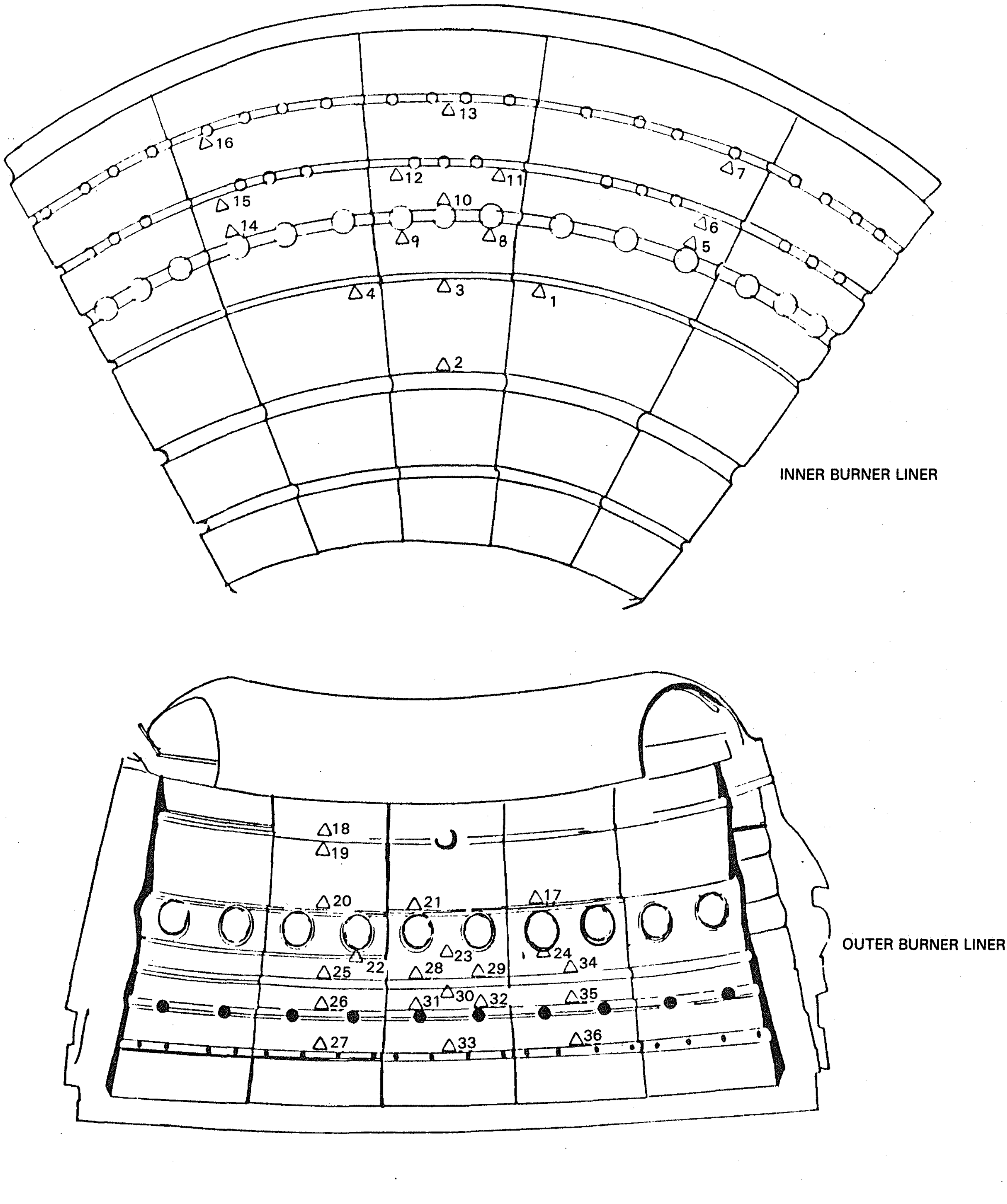


Figure 4.3.2-1 Thermocouple Sensor Locations on Segmented Liners

4.3.3 Special Rig Safety Systems

A light-off detection unit was used to indicate ignition as well as to detect the occurrence of a blowout condition. Upon the detection of a blowout, the system terminates fuel flow, thereby eliminating a hot relight situation.

Hydrocarbon detectors were installed in the inner and outer combustor shroud areas. The sensors sample flow in these environments to provide a representative measurement of hydrocarbon content. If the level exceeds a limit, an alarm is actuated and the fuel flow to the rig is automatically terminated.

4.4 DATA REDUCTION

Various types of data reduction techniques were used to calculate performance and emissions parameters. Definition of these parameters as well as their calculation methods, where applicable, is provided in Appendix A.

4.4.1 Fuel Injector Data Reduction

The fuel injector pressure and temperature data were acquired manually using conventional vertical and inclined U-tube manometers and chromel-alumel thermocouples. The data were processed to yield the following parameters:

Airflow Characterization Tests

- Rig airflows based on orifice measurements
- The differential pressure ($\Delta P/P$) across the carburetor tube assembly
- Effective flow area (AC_d), of the carburetor tube assembly and pilot injector
- Swirl number (torque/characteristic diameter x thrust), carburetor tube and pilot injector

Spray Characterization Tests

- Carburetor tube airflows from calibrations
- Carburetor tube exit velocities
- Equivalence ratio in the tube (fuel flow via turbine-type flow meters)

Jet Penetration Tests

- Primary airflows based on orifice measurements
- Primary airflows based on test section total and static pressures
- Carburetor tube airflows based on orifice measurements
- Carburetor tube airflows based on calibrations
- Carburetor tube exit air/mainstream velocity and momentum flux (ρV^2) ratios

Flow Visualization Tests

- Visual observations and various types of photography

4.4.2 Combustor Performance and Emissions Data Reduction

The data acquired through the computer system were further processed to yield the following parameters:

- o Inlet flow parameter based on measured airflow, static pressure and total static temperatures.
- o Rig flow distributions based on measured pressures and split of combustion, dilution, and cooling airflow rates.
- o Overall section and combustor liner total pressure losses.
- o Emissions indexes for carbon monoxide, total hydrocarbon, oxides of nitrogen and smoke number.
- o Environmental Protection Agency Parameters (EPAP).
- o Temperature pattern factor and radial profile.
- o Liner temperatures.

4.4.3 Advanced Liner Evaluation Data Reduction

- o The same data reduction methods and format described above were used for the advanced liner evaluation test program.

SECTION 5.0
SECTOR COMBUSTOR RIG TEST RESULTS AND ANALYSIS

5.1 FUEL INJECTOR CHARACTERIZATION TESTS

The fuel injector characterization tests served as a diagnostic tool which, in conjunction with the sector combustor rig tests, led to the aerodynamic definition of the pilot and main zone fuel injectors for the Energy Efficient Engine combustor.

5.1.1 Airflow Calibration and Fuel Spray Evaluations

Airflow calibration and fuel spray evaluations, primarily to support the main zone injector carburetor tube design, were conducted in two phases. The first included Plexiglas® carburetor tube scaled model tests to provide guidance for selecting the initial sector rig carburetor tube design. The second series of tests focused on evaluating the actual sector rig carburetor tube characteristics, including the effects of geometry variations, and candidate pilot injectors.

5.1.1.1 2X Scale Model Tests

Five carburetor tube configurations, one straight and four curved, were evaluated during these tests. The straight tube design provided a basis to assess the impact of tube curvature on performance. Figure 4.1.1-1 presents the tube design parameters.

Airflow calibrations were made to assess the effect of tube length, rate of convergence and degree of curvature. The measured effective flow areas (AC_D) and swirl numbers of these configurations are presented in Table 5.1.1-I. These results show that the effective flow area and swirl number of the baseline curved tube was only slightly lower than the straight tube values. Moreover, variations of the curved tube geometry offered no improvement in these parameters over the baseline configuration. The lower effective flow area of the increased convergence tube and the reduced swirl of the increased length tube were consistent with expectations.

Concurrently, fuel spray quality at the discharge of the tube models was visually observed and evaluated for fuel circumferential uniformity, swirl, atomization and streaking characteristics in the spray rig. The observed spray characteristics for the baseline curved and straight tubes were comparable. In conjunction with the curved carburetor tube configurations, the following variations were also evaluated: fuel injector tip axial location, floating and contoured injector guides, swirler blockage variations, and fuel injector spray pattern (flat, conical). An increased axial height swirler, which provided increased airflow relative to the baseline swirler, was also evaluated for both spray and airflow characteristics.

TABLE 5.1.1-I
SCALED MODEL CARBURETOR TUBE AIRFLOW CALIBRATION RESULTS

Config. No.	Description	Inlet Dia, D_i cm (in)	Exit Dia, D_e cm (in)	Length, L cm (in)	Discharge Angle, deg.	Effective Area (ACd) cm2 (in)2	Swirl No. (a)
1	Straight Tube	3.3 (1.3)	2.5 (1.0)	9.1 (3.6)	30	2.33 (0.37)	1.55
2	Baseline (Curved Tube)	3.3 (1.3)	2.5 (1.0)	9.1 (3.6)	50	2.14 (0.34)	1.25
3	Rapid Convergence	3.3 (1.3)	2.0 (0.8)	9.1 (3.6)	50	1.76 (0.28)	1.25
4	Increased Length	3.3 (1.3)	2.5 (1.0)	12.1 (4.8)	50	2.14 (0.34)	1.05
5	Increased Turning	3.3 (1.3)	2.5 (1.0)	9.1 (3.6)	60	2.14 (0.34)	1.25

(a) Swirl No. = $\frac{\text{Discharge Airstream Torque}}{\text{Discharge Airstream Axial Thrust X Exit Diameter}}$

Iterative testing in both rigs led to the definition of the initial sector rig main zone fuel injector, which afforded a uniform fuel spray pattern and effective spray atomization. This configuration is compared to the conceptual definition in Figure 5.1.1-1. The significant modifications for improved fuel spray characteristics are: (1) a floating injector guide with better internal aerodynamics, (2) increased fuel injector tip immersion depth, (3) increased axial height/flow capacity radial inflow swirler and (4) enlargement of the carburetor tube. The exit diameter of the carburetor tube was increased from 1.25 cm (0.5 in) to 2.0 cm (0.8 in) and the wall contour redefined to provide the same rate of tube area convergence from the radial swirler downstream face to exit as the base design.

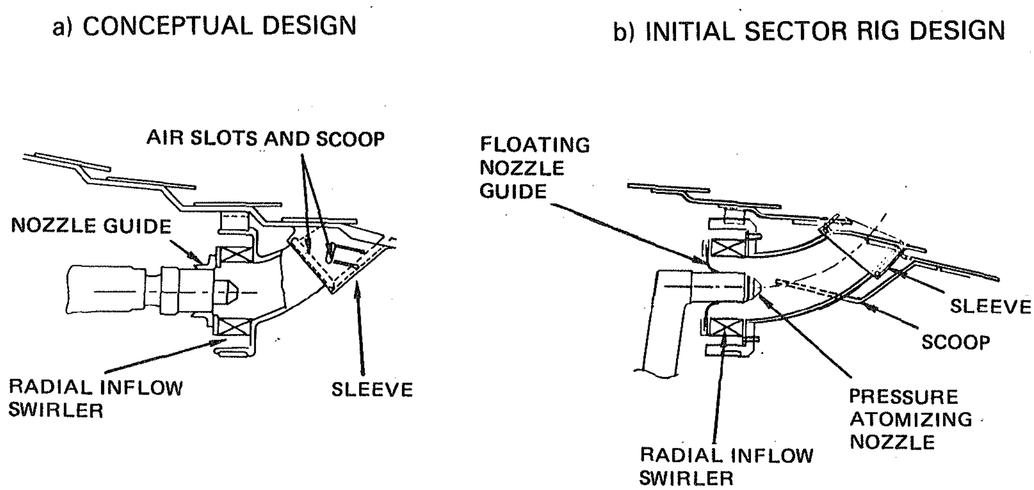


Figure 5.1.1-1 Main Zone Fuel Injector Configurations Showing Differences Between Conceptual and Modified Designs

5.1.1.2 Sector Rig Injector Tests

Calibration Tests

Airflow calibration and fuel spray characterization tests, including an evaluation of spray droplet sizes, were conducted with the sector rig pilot and main zone fuel injectors. Spray droplet characterization was performed at United Technologies Research Center using Jet-A fuel and a laser particle size/distribution analyzer system.

The pilot zone fuel injectors tested were a conventional airblast design, shown typically in Figure 5.1.1-2, in which fuel was "filmed" between two swirling air streams before being atomized. Two types of injector designs, Type A and Type B, were evaluated for airflow capacity and spray characteristics. The test results are summarized in Table 5.1.1-II.

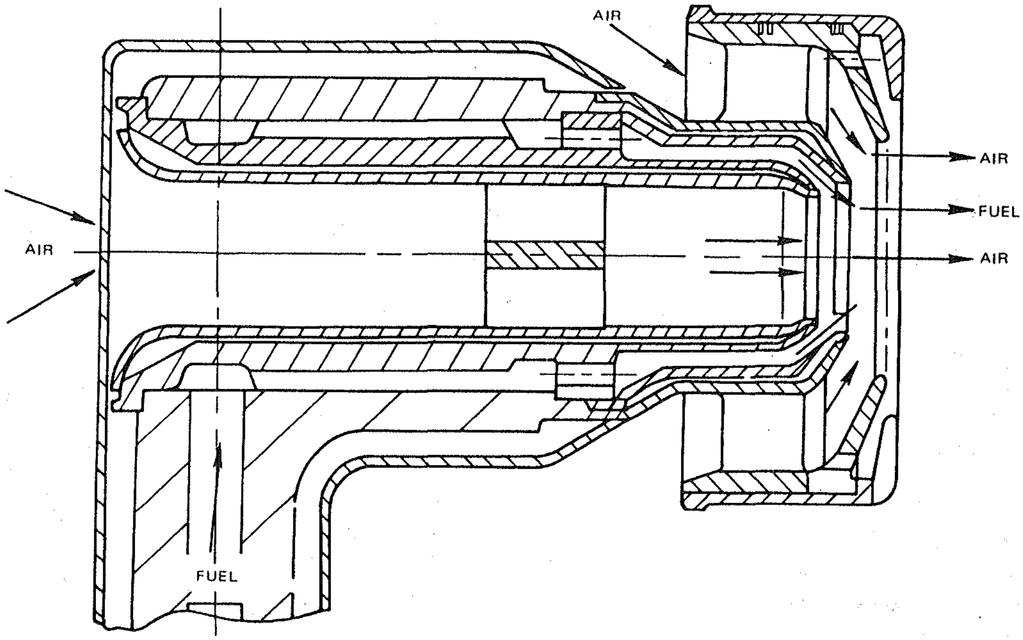


Figure 5.1.1-2 Pilot Zone Fuel Injector

TABLE 5.1.1-II
PILOT ZONE FUEL INJECTOR CHARACTERISTICS

Injector	Effect. Area (AC_d) cm^2 (in^2) Total	Inner	Outer	Swirl Strength cm (in) (Torque/Thrust)	Sauter Mean Diameter SMD (microns) Simulated Conditions Idle	Starting
Goal	(*)	(*)	(*)	1.3 (0.5)	50	100
Type A	1.83 (0.29)	0.52 (0.08)	1.29 (0.20)	1.5 (0.6)	22	110
Type B	1.70 (0.27)	0.19 (0.03)	1.47 (0.23)	0.7 (0.3)	32	90

(*) Combined AC_d = 1.827 to 2.016 cm^2 (0.290 to 0.320 in^2)

The effective area of the two injectors at the minimum or slightly below the goal was considered acceptable for initial hot testing.

Both injector types exhibited acceptable droplet size. Figure 5.1.1-3 shows a photograph of the Type B injector spray at the idle test condition that illustrates the good pilot injector spray quality. The swirl strength of injector Type B, however, was judged too low for good combustion stability. This result was corroborated during subsequent sector rig testing. Consequently, it was modified by changing the inner and outer passage areas 0.19 and 1.052 cm^2 (0.03 and 0.167 in^2), respectively, to increase the swirl strength to 1.25 cm (0.5 in). The modified injector incorporated a reduced effective area (1.26 cm^2 (0.20 in^2)), based on early sector rig emission trends.

Testing with the main zone fuel injectors was conducted in a similar manner to those with the pilot zone injectors. An exploded view of the main zone fuel injector assembly is shown in Figure 5.1.1-4. A typical carburetor tube exit jet with a uniform fuel/air pattern and small fuel droplets is illustrated in Figure 5.1.1-5.

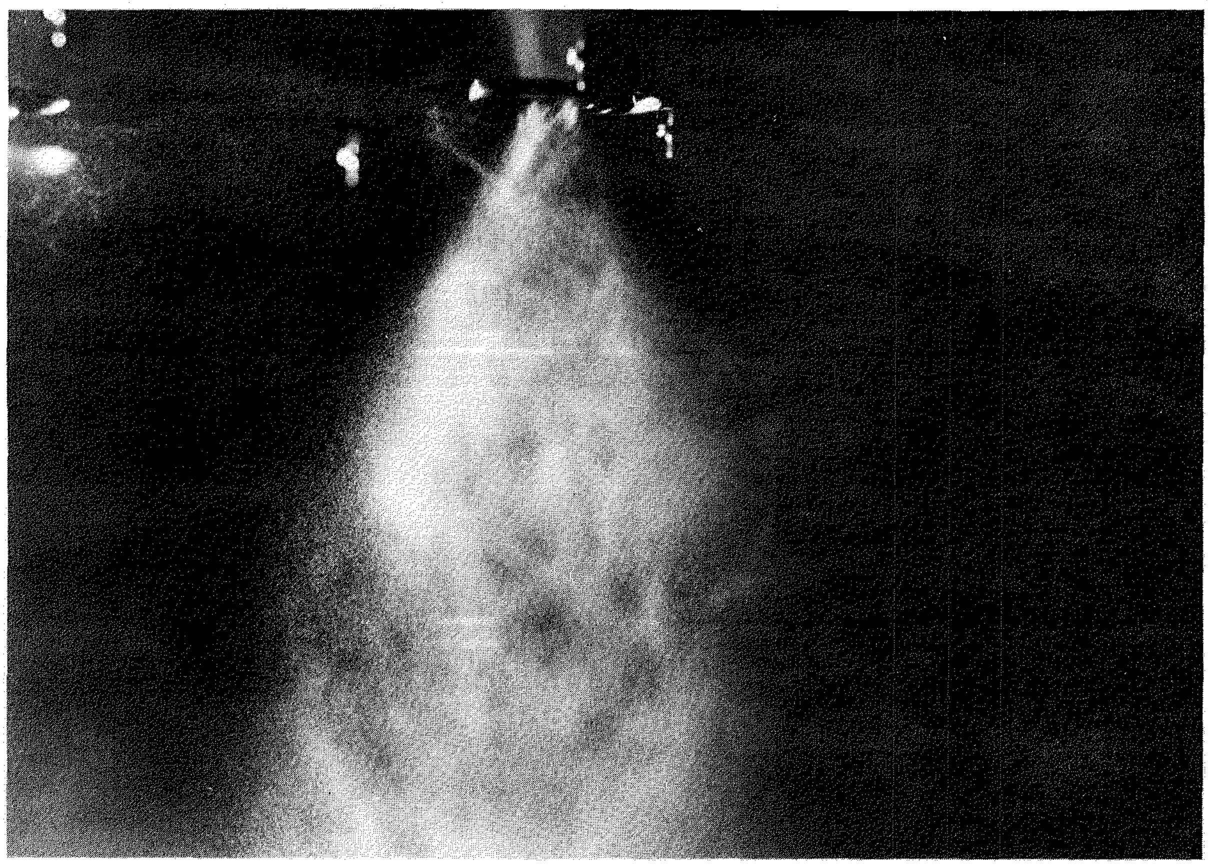


Figure 5.1.1-3 Type B Pilot Injector Spray Characteristics at Simulated Idle Test Conditions

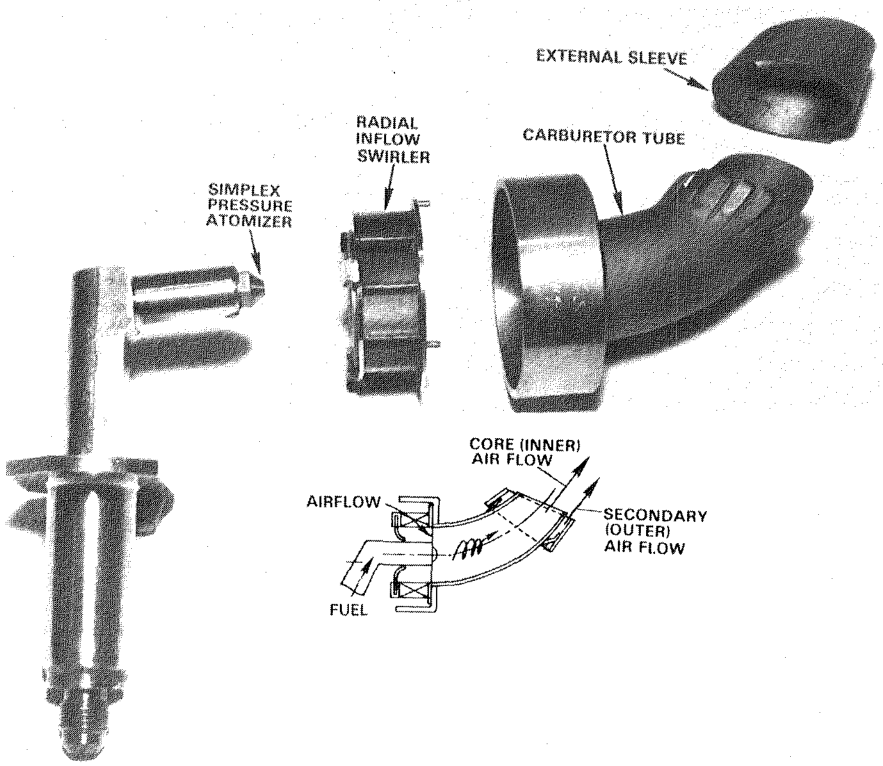


Figure 5.1.1-4 Main Zone Fuel Injector Assembly Features

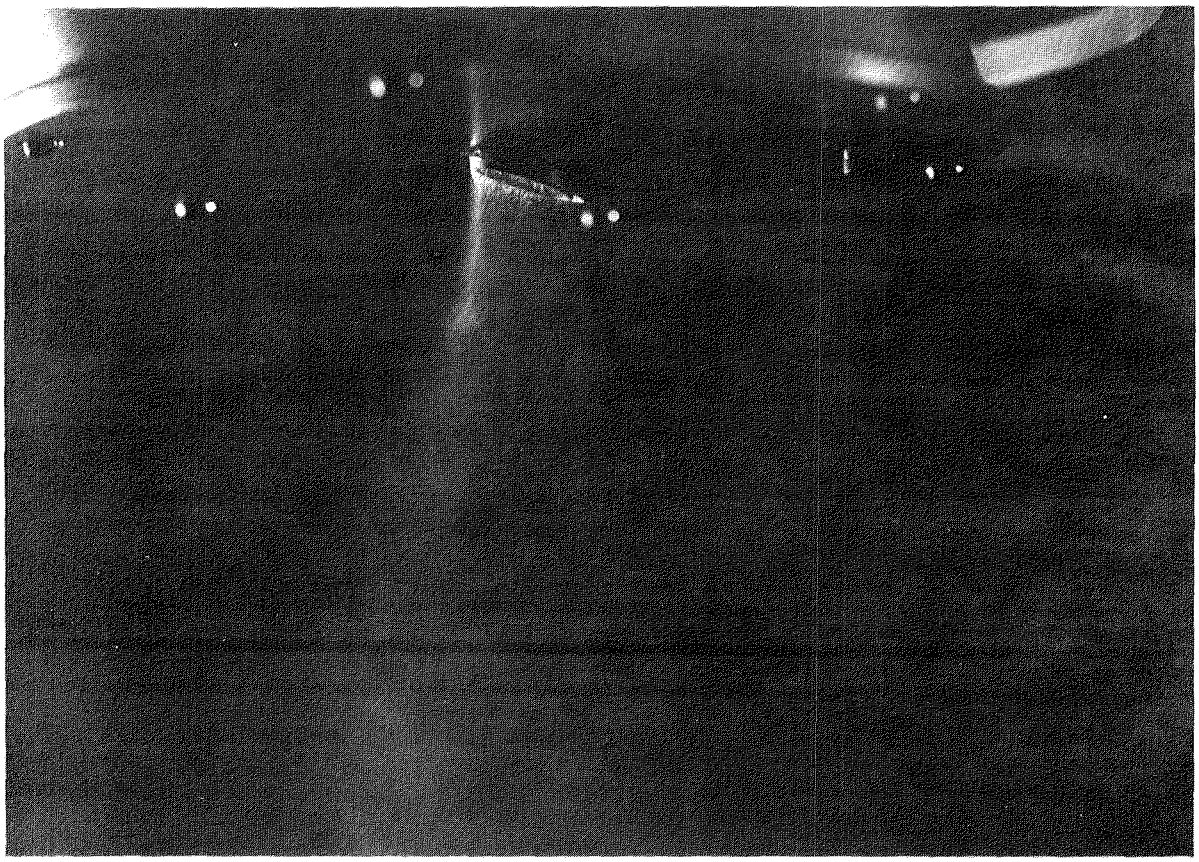


Figure 5.1.1-5 Sector Rig Carburetor Tube (1.295 cm (0.510 in) Vane Height Swirler External Sleeve Fingers) Fuel Spray Pattern at Simulated Sea Level Takeoff Conditions

The effect of tube core airflow on fuel droplet size is shown in Figure 5.1.1-6. Fuel droplet size decreased with increasing core airflow velocity and with decreasing fuel flow rate. As indicated, increasing the height of the vane in the radial inflow swirler does not affect droplet size for the same core exit airflow velocity. At the design core airflow exit velocity, 79 to 90 kg/sec (175 to 200 ft/sec) at sea level takeoff conditions, acceptable fuel droplet size was demonstrated.

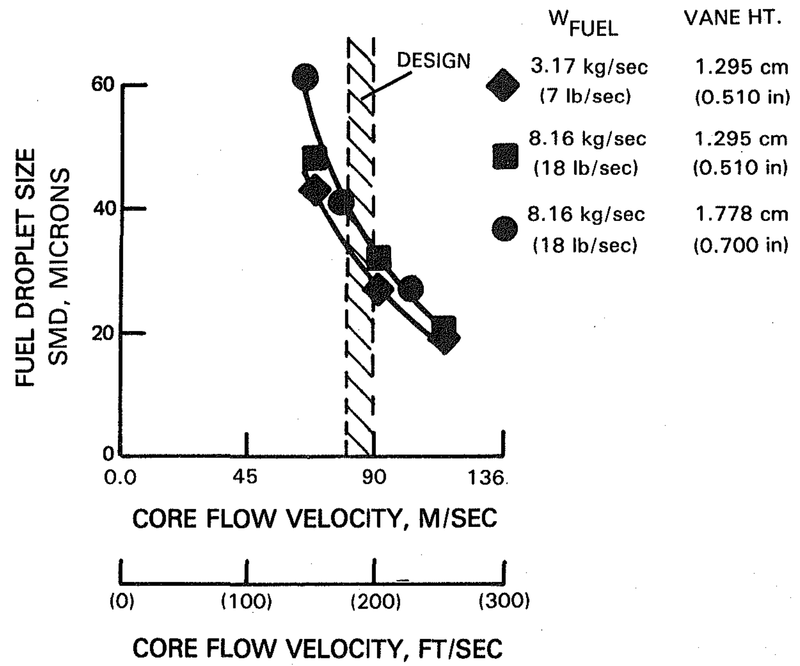


Figure 5.1.1-6 Effect of Tube Core Airflow on Fuel Droplet Size

Figure 5.1.1-7 shows the effect of secondary to core airflow split on droplet size for three different values of core exit velocity. Droplet size is reduced substantially by increasing the ratio of secondary to total airflow up to approximately 40 percent. In addition, there is a negligible decrease in droplet size at levels greater than 40 percent. On the basis of these results, the optimum fuel droplet size is 35 to 40 microns for the 79 to 90 kg/sec (175 to 200 ft/sec) design velocity.

Visual Spray Evaluations

Spray characterization tests were conducted in stand X-408 with sector rig carburetor tube hardware. Test air and fuel flows through the tube simulated engine approach and sea level takeoff conditions. Fuel injector placement sensitivity testing was also performed with the carburetor tube assembly.

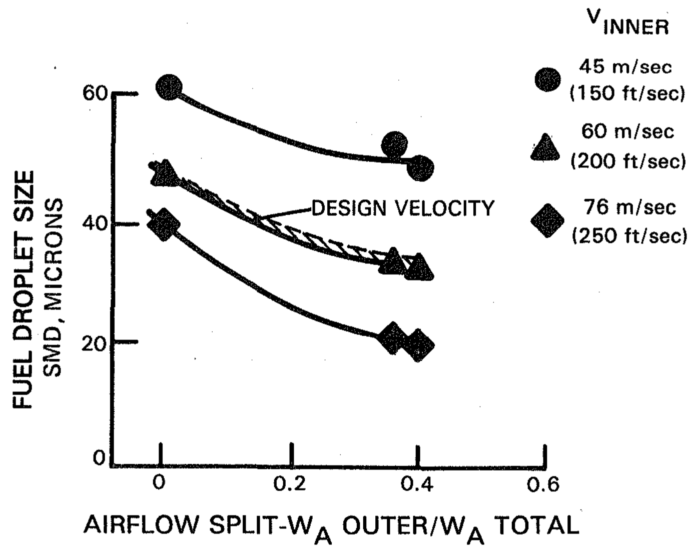


Figure 5.1.1-7 Effect of Secondary (Outer Sleeve) Airflow on Fuel Droplet Size

Engine inboard and outboard radial locations of the injector as well as axial immersion were qualitatively documented in terms of their respective effect on exit spray uniformity, swirl strength and degree of atomization. With respect to the base case (injector centered in 1.295 cm (0.510 in) vane height radial inflow swirler), radial deflections of ± 0.254 cm (± 0.100 in) and axial immersions of ± 0.635 cm (± 0.250 in) were tested. Observations made during these tests are presented below.

- o Fuel droplet size was consistent throughout the entire range of testing.

- o With respect to the base case, additional injector immersion of 0.635 cm (0.250 in) improved spray uniformity at approach, confirming large scale model test results.

- o Exit spray uniformity, with baseline immersion, was improved with a 1.778-cm (0.700-in) swirler in the carburetor tube assembly, which passed 10 percent more airflow than the baseline 1.295-cm (0.510-in) swirler.

- o The exit spray cone angle was increased by the removal of the secondary airflow.

- o Radial inboard movement of the injector is preferrable to radial outboard movement in terms of fuel spray uniformity at sea level take-off. This preference was applied in defining the design radial location of the fuel injector in the carburetor tube for the combustor component.

5.1.2 Jet Penetration Tests

Tests were conducted to investigate the penetration characteristics of the main zone carburetor tube fuel injector exhaust jets into the combustion chamber. The intent was to ascertain the trajectory and potential for penetration to the inner liner, which is undesirable for performance, durability and emissions considerations.

An initial series of tests was conducted to obtain comprehensive single jet penetration characteristics using large scale Plexiglas® models of carburetor tubes, both with and without radial flow swirlers, and a plane orifice (e.g., dilution) jet. Penetration was mapped, using both visualization and hot wire anemometer traverses, for jet to combustion gas velocity ratios (i.e., $U_j/U = 2,4,6$), which encompass the engine level velocity and momentum flux ratios. The center line of the three types of jets, at a velocity ratio of 4, is shown in Figure 5.1.2-1. The relative penetration among the types of jets remains the same at the other tested velocity ratios. However, the absolute penetration is greater at a velocity ratio of 6 and less at the lower value. Although the penetration of the Energy Efficient Engine carburetor tube jet with swirler is less than that for jets without swirlers, possible overpenetration of the carburetor tube jet to the inner liner was indicated.

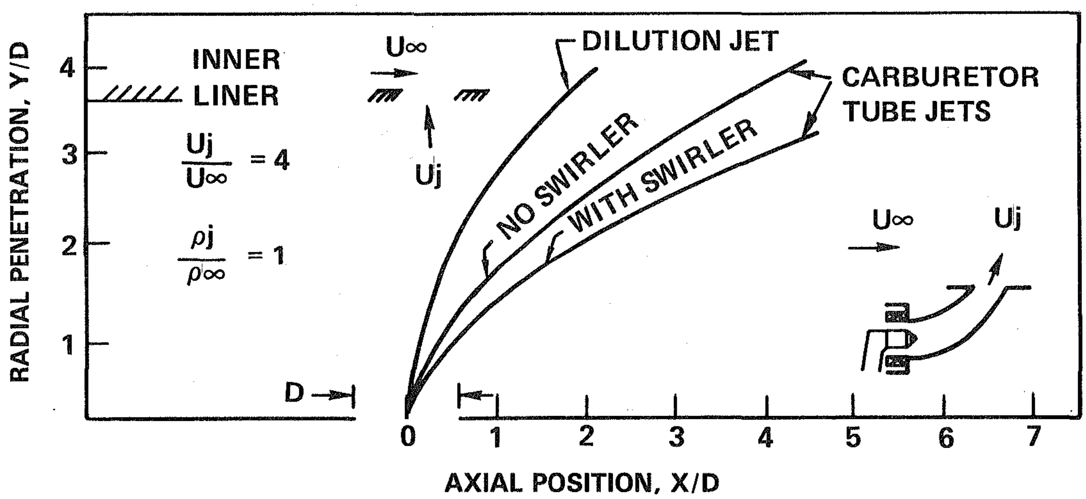


Figure 5.1.2-1 Flow Jet Penetration Centerlines for Three Types of Jets

A series of two-dimensional flow visualization tests was conducted later using the modified sector rig carburetor tubes shown in Figure 5.1.2-2 to further investigate exit jet penetration characteristics. The test rig was designed to accommodate three carburetor tubes at the design circumferential spacing. Jet penetration was documented using Di (2-Ethyl Hexyl) Phathalate (DOP) to seed the carburetor tube airflow. A 50 mw laser supplied energy to illuminate the seed and photographs normal to the centerline of the center tube were taken to show the resulting flows. Geometric variables investigated included both single and multiple jets, the effect of opposing (inner) liner dilution holes, and the effect of swirling versus nonswirling carburetor tube secondary airflow (Figure 5.1.2-3).

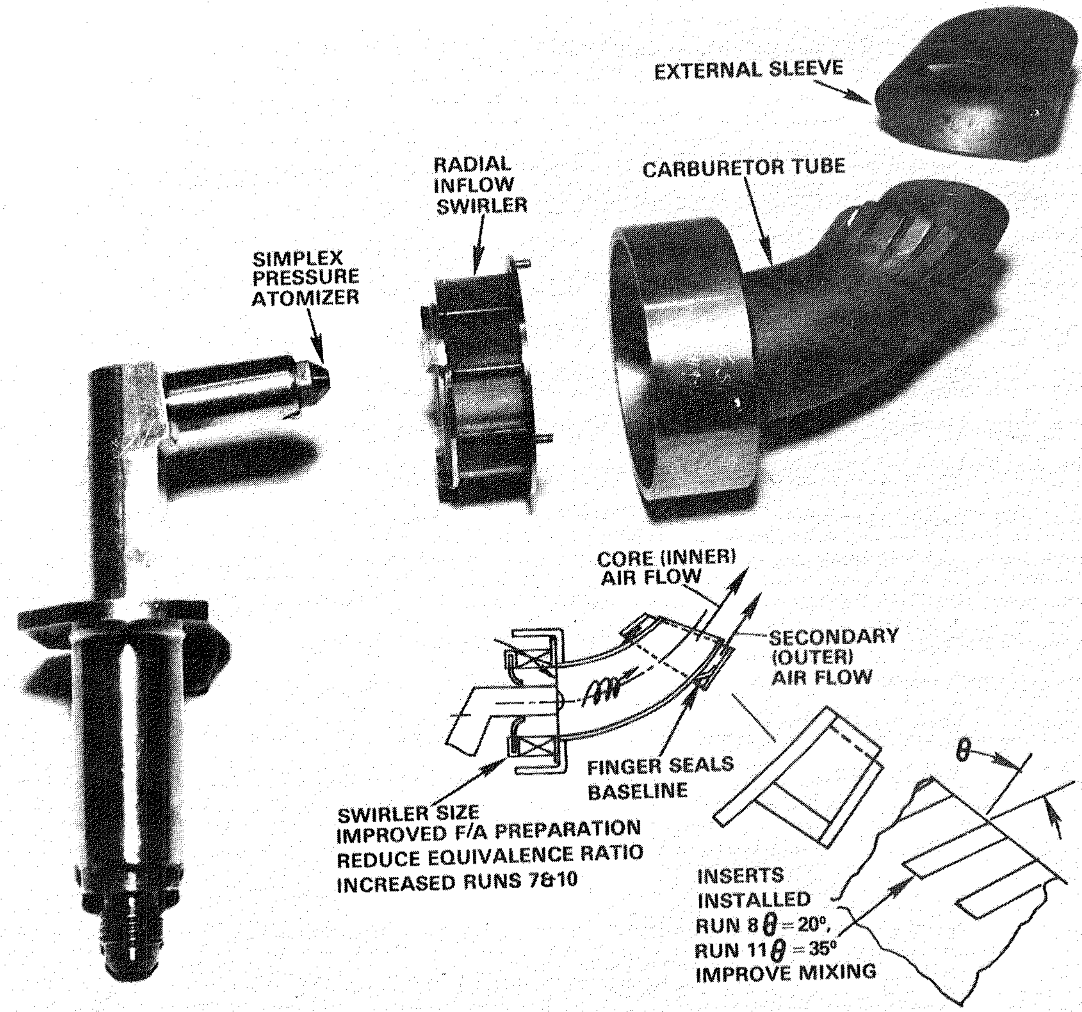
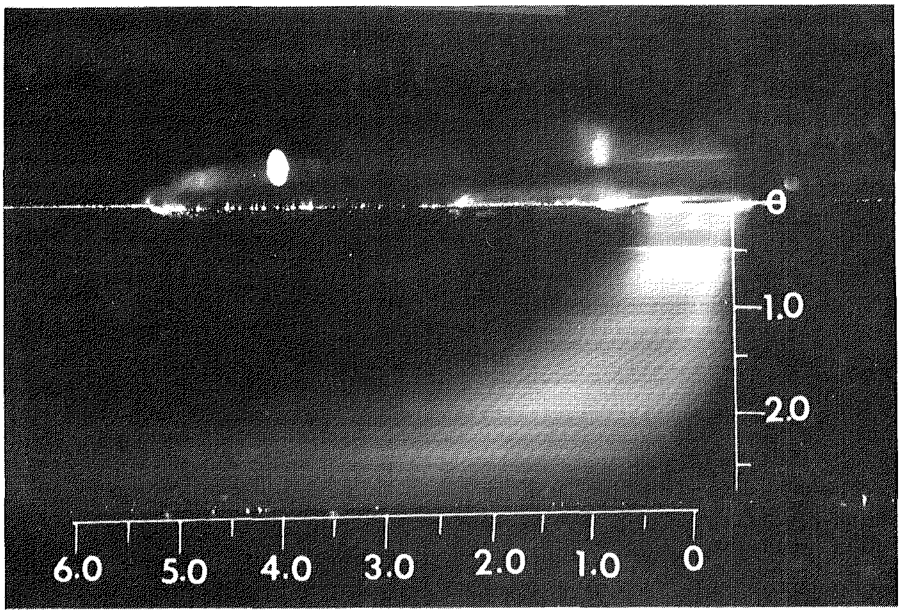


Figure 5.1.2-2 Main Zone Fuel Injector Assembly Features, Showing Modified Secondary Airflow Sleeve (Swirlers)

Test results from the single and multiple carburetor tube configurations, as shown in Figures 5.1.2-3 and -4, indicate significantly reduced penetration with the three jet configuration. This configuration, which simulates the ratio of total normal jet cross-sectional area to duct cross flow area in the Energy Efficient Engine combustor, increases blockage to the mainstream flow and hence mainstream velocity relative to the single jet resulting in the reduced jet penetration. This testing confirmed that the multi-jet test configuration was required to adequately simulate the Energy Efficient Engine combustor conditions in these tests.

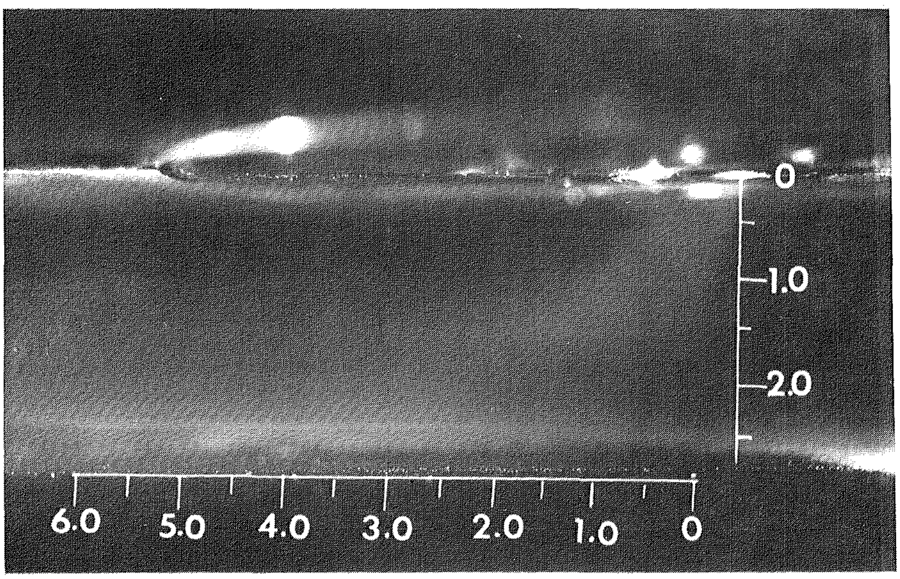
The penetration centerline for the center carburetor tube is presented in Figure 5.1.2-5 for the three jet to mainstream velocity ratios tested. The velocity ratio of 3.4 simulates the sector rig combustor design jet to main stream momentum ratio at the sea level takeoff condition. This trace, derived from the penetration pattern shown in Figure 5.1.2-4, indicates a potential for the jet to partially impinge on the inner liner wall.



Y/D

AXIAL POSITION X/D

Figure 5.1.2-3 Single Carburetor Tube Discharge (1.295 cm (0.510-in) Vane Length Swirler), $uj/\bar{u}$ = 3.4, Sleeve Fingers



Y/D

AXIAL POSITION X/D

Figure 5.1.2-4 Center Carburetor Tube Discharge for Multiple Jets (Same jet design as in Figure 5.1.2-3)

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Commercial Products Division

In reply please refer to:
WBG:WS (0317K) 118-35
LC-82-13

1 March 1983

To: Distribution

Subject: Energy Efficient Engine Sector Combustor Rig Test Program Technology Report, CR-167913

Gentlemen:

The enclosed report is furnished for your information.

Sincerely yours,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group
Commercial Engineering

W B Gardner
W.B. Gardner
Program Manager

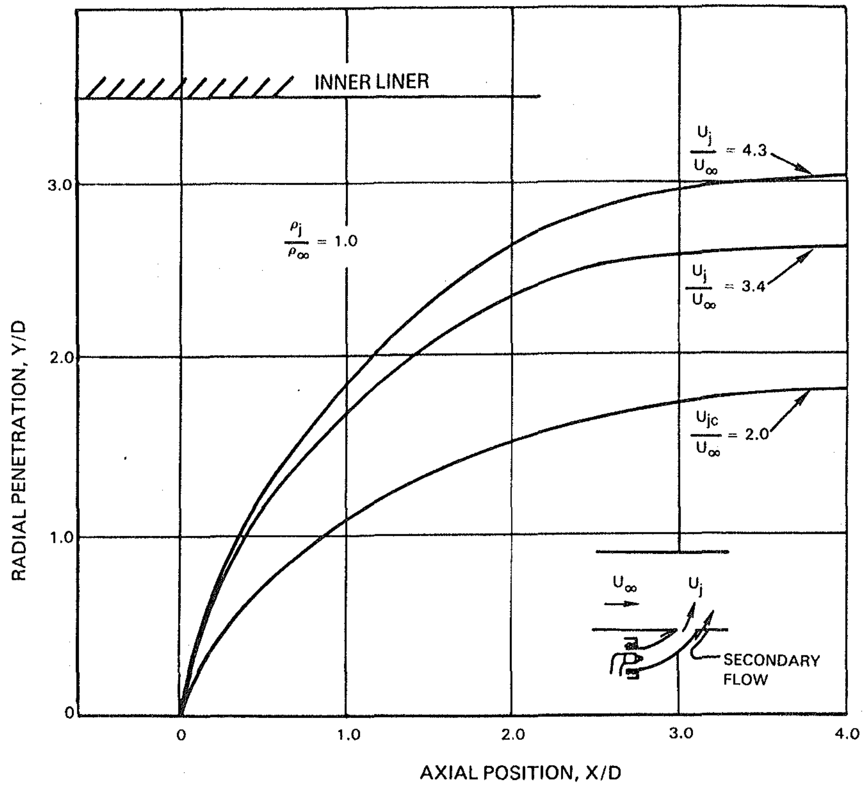


Figure 5.1.2-5 Sector Rig Baseline Carburetor Tube Jet Penetration Characteristics (Center Tube)

Subsequent tests were performed to assess the impact of opposing inner wall dilution holes and carburetor tube secondary air swirl on the main zone injector jet penetration. As indicated in Figure 5.1.2-6, dilution holes can be used to effectively reduce carburetor tube jet penetration. Swirling of the secondary (sleeve) air, which is desirable for improved core and secondary stream mixing, also offers some potential to reduce jet penetration. This is indicated by the comparative jet centerline penetration data in Figure 5.1.2-7. Both of these features, which demonstrated beneficial trends, were incorporated in the main zone fuel injector configuration for the final combustor component design that evolved from the Sector Combustor Rig Test Program.

5.1.3 Flow Visualization Tests

5.1.3.1 Two-Dimensional Flow Visualization Tests

Testing of a diffuser/combustor two-dimensional, full-size model in a water tunnel rig provided a qualitative evaluation of diffuser/combustor airflow characteristics. Visual observations, using dye and bubble injection techniques, indicated acceptable pilot zone recirculation and smooth combustor hood and inner/outer shroud annuli flow characteristics. A test with a smaller diffuser dump volume, considered as a weight reduction concept, demonstrated inferior combustor and annuli flow characteristics.

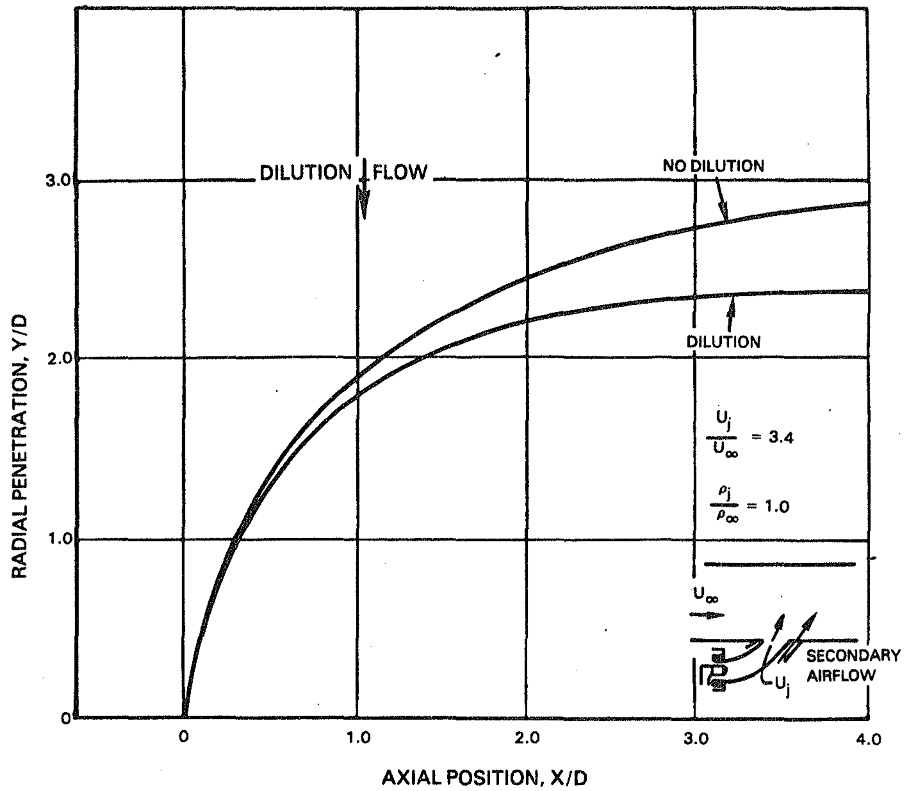


Figure 5.1.2-6 Effect of Inner Liner Dilution Hole on Sector Rig Carburetor Tube Jet Penetration (Three tube array, center tube shown)

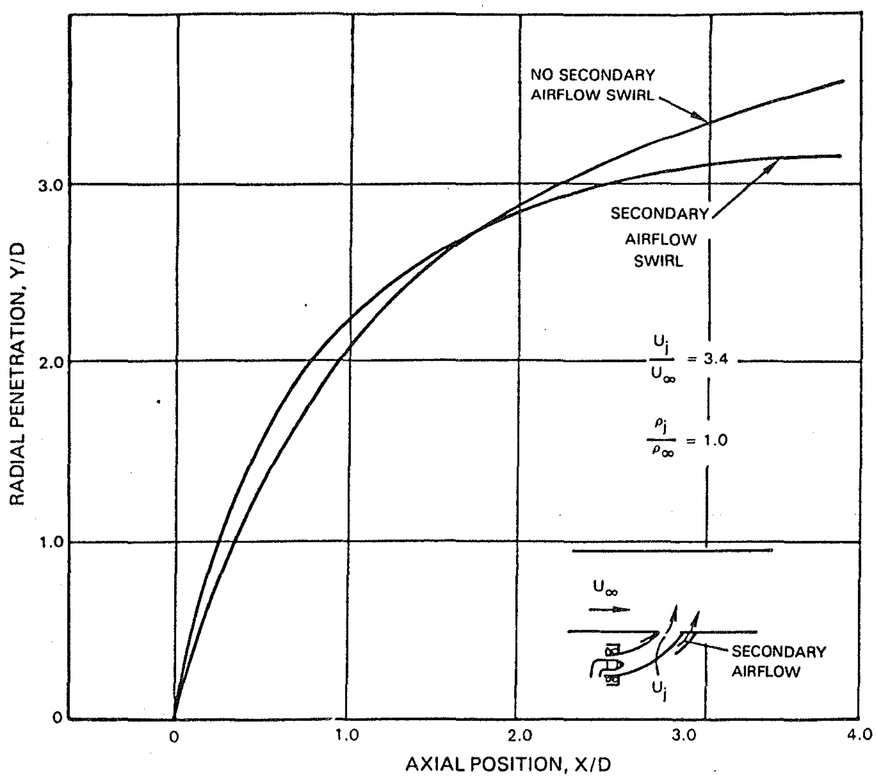


Figure 5.1.2-7 Effect of Swirling Secondary (Sleeve) Air on Sector Rig Carburetor Tube Jet Penetration (Center Tube)

5.1.3.2 Carburetor Tube Internal Flow Characteristics

Flow visualization tests were conducted to investigate the internal flow field of the sector rig carburetor tube design. A sector rig main zone fuel injector assembled with a Pyrex carburetor tube was mounted in a plenum chamber and flow tested in a low pressure airflow stand. The test was conducted at a tube exit velocity corresponding to takeoff conditions V=53 m/sec (V=175 ft/sec), and with an equal mixture of Benzyl Alcohol and Ethelyne Glycol to simulate fuel flow. The seeding/laser photographic technique previously discussed was used to document tube internal flow characteristics. The tests indicated no stalled or recirculating flow patterns in the tube and showed the simulated fuel to be rapidly centrifuged out and uniformly distributed on the carburetor tube wall.

5.1.4 Fuel Injector Characterization Test Summary

The fuel injector program, in conjunction with the sector rig effort, was instrumental in evolving design improvements for the main zone carburetor tube injector and pilot injector designs. The significant carburetor tube modifications included: a floating injector guide with better internal aerodynamics, increased fuel injector tip immersion depth, enlargement of the carburetor tube, and an increased axial length and flow capacity radial inflow swirler. Testing provided a characterization of pilot and main injector fuel spray characteristics, including uniformity, penetration, atomization, and definition of swirl strength and effective area for the carburetor tube and the pilot zone injectors.

5.2 SECTOR COMBUSTOR RIG EMISSIONS AND PERFORMANCE TESTS

This part of the sector combustor rig program was successful in demonstrating that the Energy Efficient Engine combustor design is capable of meeting all performance goals and nearly all emissions goals. Although the emissions goal for oxides of nitrogen was not met, a significant reduction was achieved when compared to current gas-turbine engine combustor levels.

A total of sixteen tests, including two altitude relight evaluations, was performed using the sector rig with a conventional, sheet metal louvered liner. Table 5.2-I presents a summary of each test configuration. Key combustor airflows and zone equivalence ratios for each configuration are summarized in Table 5.2-II. The results of these tests, in terms of exhaust emissions, aerothermal performance, safety, and mechanical performance, are discussed in the following sections. In addition, a description of the test configurations is contained in Appendix B and a test data summary sheet for each configuration is contained in Appendix C.

5.2.1 Exhaust Emissions Reduction Tests

Initial combustor testing concentrated on achieving low power emissions reductions. Certain pilot zone modifications were evaluated to determine the effect on reducing carbon monoxide and unburned hydrocarbons at idle conditions. These modifications consisted of changes to airflow schedule, the flow split between the fuel injector inner/outer airblast passages, and fuel injector design.

TABLE 5.2-I
SECTOR COMBUSTOR RIG PERFORMANCE AND EMISSIONS
SUMMARY OF TEST CONFIGURATIONS

Run No.	Type	Purpose/Configuration
---	Shakedown	Check out rig installation, secondary flow systems, and instrumentation Initial light-off and pilot/main zone fuel injector staging
2	Emissions/Perf	Baseline performance -- Type A pilot injectors
3	Emissions/Perf	Baseline performance --Type B pilot injectors
4	Emissions/Perf	Changes relative to Run 2 configuration: o Reduced pilot zone airflow-increased equivalence ratio (0.8 to about 0.9) o Reduced (about 3 percent combustion air) pilot zone cooling level o Reduced (about 6 percent combustion air) main zone dilution air o Increased (about 3 percent combustion air) main zone cooling level
5	Emissions/Perf	Changes relative to Run 4 configuration: o Reduced pilot zone injector airflow - increased equivalence ratio (0.9 to about 1.1) o Main zone unchanged
6	Emissions/Perf	Changes relative to Run 5 configuration: o Reduced (about 5 percent combustion air) main zone dilution air o Pilot zone unchanged
7	Emissions/Perf	Changes relative to Run 6 configuration: o Increased carburetor tube core airflow by about 20 percent o Reduced the AC_d of the pilot injector (Type A) inner passage by about 30 percent o Reduced inner louver 6[(1)] cooling about 2 - percent combustion airflow
8	Emissions/Perf	Changes relative to Run 7 configuration: o Installed 20-degree swirlers in carburetor secondary air passage o Decreased pilot injector blockage

(1) Refer to Figure 3.5.2-2 for location.

TABLE 5.2-I (Continued)
SECTOR COMBUSTOR RIG PERFORMANCE AND EMISSIONS
SUMMARY OF TEST CONFIGURATIONS

Run No.	Type	Purpose/Configuration
9	Emissions/Perf	Changes relative to Run 8 configuration: o Reduced inner louvers 5 and 6 cooling air about 35 and 45 percent, respectively o Added 0.7 x 1.7 cm (0.3 x 0.7 in) in dilution slots in inner louver 7
10A	Emissions/Perf	Changes relative to Run 9 configuration: o Increased carburetor tube core airflow by about 10 percent o Reduced carburetor tube length by about 10 percent o Revised outer and inner liner dilution air schedule
10B	Emissions/Perf	Changes relative to Run 10A configuration: o Installed redesigned pilot fuel injectors
11	Emissions/Perf	Changes relative to Run 9 configuration: o Installed redesigned pilot fuel injectors o Installed 35-degree insert type swirlers in carburetor secondary air passage o Modified downstream dilution schemes to cause radial exit temperature profile shift
12	Alt Relight	Used Run 10 configuration and Type B pilot injector
13	Alt Relight	Used Run 10 configuration and Type A pilot injector
14	Emissions/Perf	Evaluated sensitivity to the diffuser inlet pressure profile with Run 11 configuration (modified Type B pilot injector)
15	Emissions/Perf	Added approximately 6 percent dilution air (pilot exit) to reduce oxides of nitrogen at approach Added approximately 2 percent dilution air in outer louvers 8 and 9 to trim exit radial temperature profile
16	Emissions/Perf	Reduced hood flow inlet area approximately 25 percent
17	Emissions/Perf	Test run canceled -- not necessary to satisfy program requirements

TABLE 5.2-II

SUMMARY OF KEY AIRFLOW PERCENTAGES (% WAB)
AND ZONE EQUIVALENCE RATIOS (Ø)
(For Configuration Evaluated During Sector Combustor
Rig Emissions and Performance Test)*

	Runs 2 & 3	Run 4	Run 5	Run 6	Run 7	Run 8
PILOT ZONE						
Nozzle	12.8	14.0	10.5	11.0	9.2	10.6
Guide Purge	3.8	1.1	1.0	1.1	1.1	1.0
40% Heatshield Cooling Flow	1.4	1.6	1.5	1.6	1.6	1.5
Idle (Peak)	0.8	0.85	1.1	1.0	1.2	1.1
MAIN ZONE						
Carb Tube	27.7	31.6	33.2	32.0	35.1	29.6
50% Inner Diameter Dilution	3.5	1.4	1.5	0.0	1.3	1.5
30% Outer Diameter Dilution	2.4	1.9	2.1	1.3	1.4	2.2
SLTO	0.81	0.74	0.74	0.81	0.72	0.81
Liner Cooling	37.5	40.3	41.8	41.0	39.0	45.0

	Runs 9	Run 10B	Run 11	Run 14	Run 15	Run 16
PILOT ZONE						
Nozzle	10.0	8.9	10.5	10.1	9.52	9.30
Guide Purge	0.97	0.96	1.25	1.21	1.13	1.1
40% Heatshield Cooling Flow	1.4	1.4	1.8	1.8	1.65	1.6
Idle (Peak)	1.2	1.3	1.0	1.1	1.2	1.2
MAIN ZONE						
Carb Tube	27.4	28.8	30.0	30.4	29.9	31.14
50% Inner Diameter Dilution	8.3	6.8	4.8	4.8	5.8	5.9
30% Outer Diameter Dilution	1.9	2.1	2.0	2.04	2.2	2.14
SLTO	0.72	0.72	0.74	0.73	0.71	0.69
Liner Cooling	35.4	36.3	37.45	37.5	36.5	35.8

*Exclusive of Altitude Relight Configurations (12 and 13)

Subsequent tests were directed towards optimizing the main zone for efficient main zone fuel staging at the approach condition and reducing oxides of nitrogen at high power operation. Main zone modifications included changes to carburetor tube design and airflow schedule. The effect of pilot to main zone fuel split was investigated for all configurations.

5.2.1.1 Pilot Zone Optimization

The pilot zone must provide low levels of carbon monoxide and unburned hydrocarbons during single stage operation at idle, while ensuring adequate stability during dual stage operation at higher power conditions. Experience gained from previous combustor technology efforts, such as the Experimental Clean Combustor Program (Ref. 2), has shown that for a given combustor design (volume and dome height fixed), the parameters that most affect carbon monoxide and unburned hydrocarbon emissions are fuel/air preparation and overall zone stoichiometry. Cooling flows in intimate contact with combustion reactants have also been found to affect emissions. Results pertaining to the investigation of these parameters are presented in the following sections.

Pilot Zone Airflow Schedule Optimization

The pilot zone airflow schedule required for high combustion efficiency at idle conditions was determined early in the program. Three configurations were modified for successive increases in zone equivalence ratio (ϕ) and assessed for emissions and performance. The configurations are summarized in Table 5.2.1-I (runs 2 through 5).

Emissions trends at the design idle condition are shown in Figure 5.2.1-1 for each configuration. As indicated, increasing peak zone equivalence ratio resulted in significant reductions in both carbon monoxide and total unburned hydrocarbons. This peak equivalence ratio occurs in the immediate vicinity of the fuel nozzle and is affected by the inflow of air around the nozzle and fuel droplet vaporization.

On the basis of shakedown test results, combustion air was eliminated from the inner and outer pilot zone liner walls to increase the overall zone equivalence ratio to 0.8 and prevent premature quenching of the combustion reaction in run 2. Zone equivalence ratio was again increased to 0.9 in run 4 by eliminating superfluous fuel injector guide airflow. This was accomplished by modifying the injector guide flotation arrangement to eliminate expansion slots which admit approximately 7 percent of zone combustion air. In addition, the pilot zone cooling level was reduced by approximately 3 percent of the combustion airflow. As indicated in Figure 5.2.1-1, these revisions contributed to an additional reduction in emissions.

In run 5, pilot injector (Type A) inner and outer airblast passage airflows were reduced by installing blockage rings at the entrance of both passages. This resulted in an increase in zone equivalence ratio from 0.85 to 1.10 and produced the lowest level of emissions at the design fuel/air ratio (0.0098). These results show that a pilot zone equivalence ratio near or at the 1.1 value provides effective emissions control at idle.

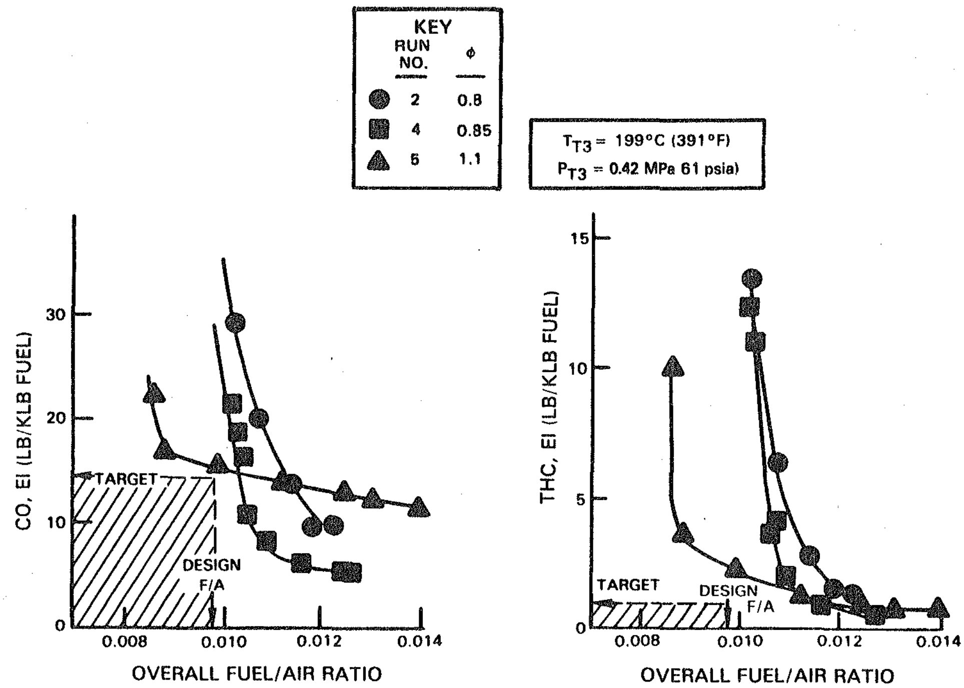


Figure 5.2.1-1 Comparison of Emissions Reductions at Idle Condition by Changing Equivalence Ratio in Pilot Zone

Pilot Zone Injector Design Optimization

The baseline performance of the pilot zone fuel injector configurations (Types A and B) was investigated during test runs 2 and 3. As discussed earlier in Section 5.1.1, these injectors exhibited similar flow and spray characteristics, with the exception that the swirl strength of injector Type B was approximately one half of injector Type A. Testing was performed using identical front end and liner features with each injector. The results in Figure 5.2.1-2 clearly show that emissions at idle are significantly higher with the lower swirl strength Type B injector, thereby demonstrating the importance of swirl in establishing the recirculation zone for good pilot zone performance.

The effect on emissions by varying the airflow split between the inner and outer pilot injector airblast passages was evaluated in run 8 by performing sequential tests with three pilot injector variations. Blockage rings installed at the inlet of the inner and outer swirler passages were employed to vary the airflow rates. The different area variations tested along with the corresponding results are presented in Figure 5.2.1-3. As shown, a significant reduction in idle emissions was achieved by reducing the inner passage tube flow area.

The information obtained from these investigations provided the guidance to reconfigure the pilot injector in terms of optimum swirl strength and passage flow area. The measured swirl strength was 1.2 cm (0.5 in). Passage area was 0.19 and 1.077 cm^2 (0.03 and 0.167 in^2) for the inner and outer passages, respectively.

This redesigned nozzle was evaluated during test run 10, and the results are presented in Figure 5.2.1-4. The results substantiate the design changes, showing that the injector produced the lowest emissions at idle.

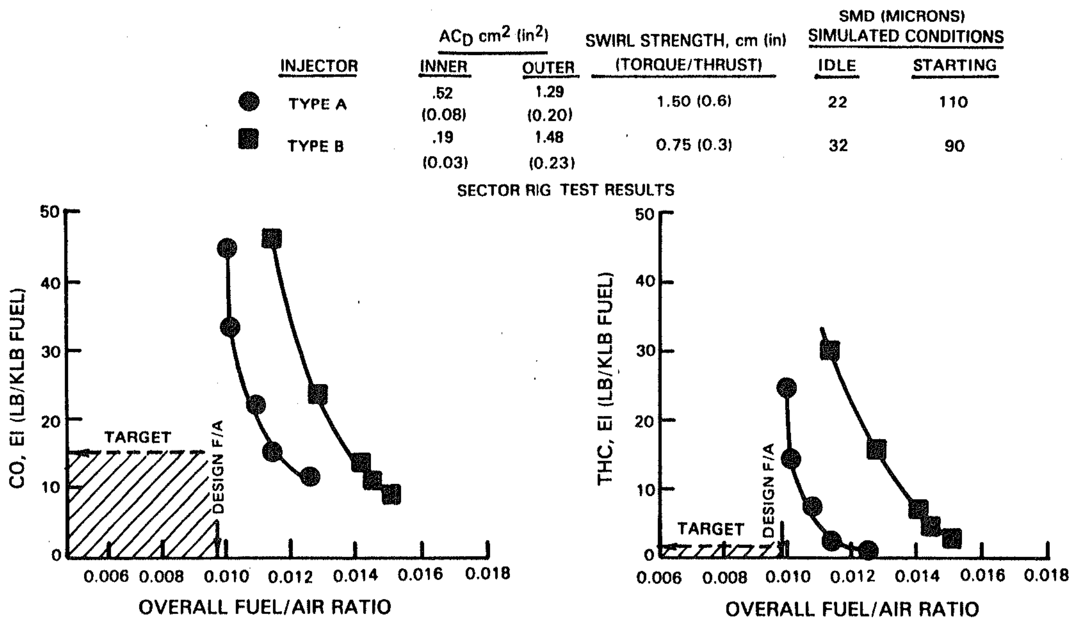


Figure 5.2.1-2 Comparison of Idle Emissions for Types A and B Pilot Zone Fuel Injectors

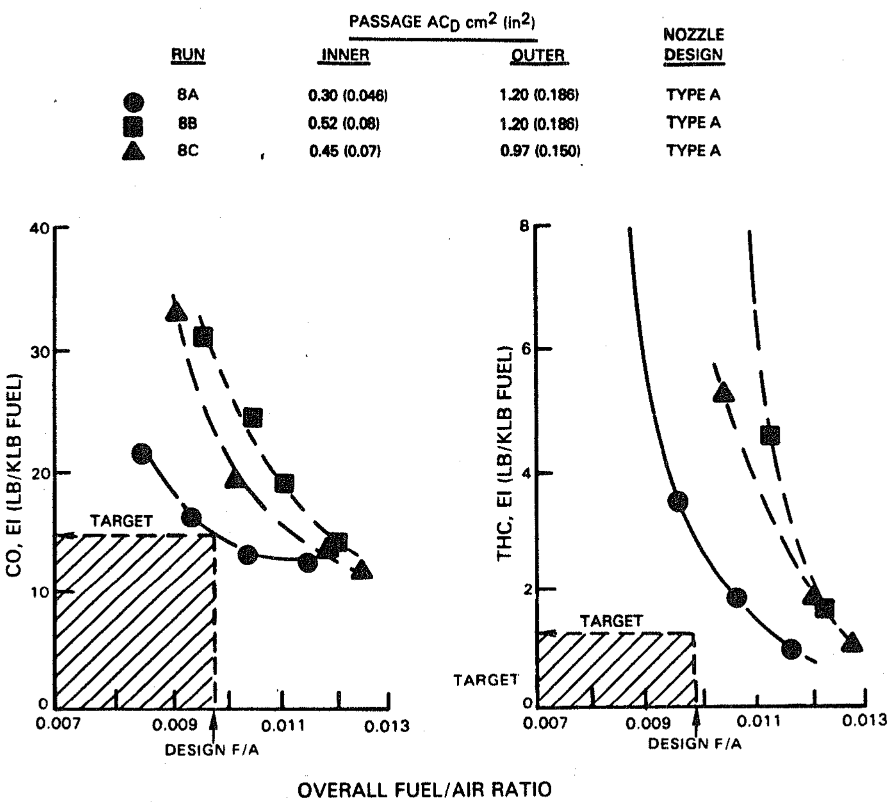


Figure 5.2.1-3 Comparison of Idle Emissions by Varying Pilot Zone Fuel Injector Inner/Outer Passage Area (AC_d)

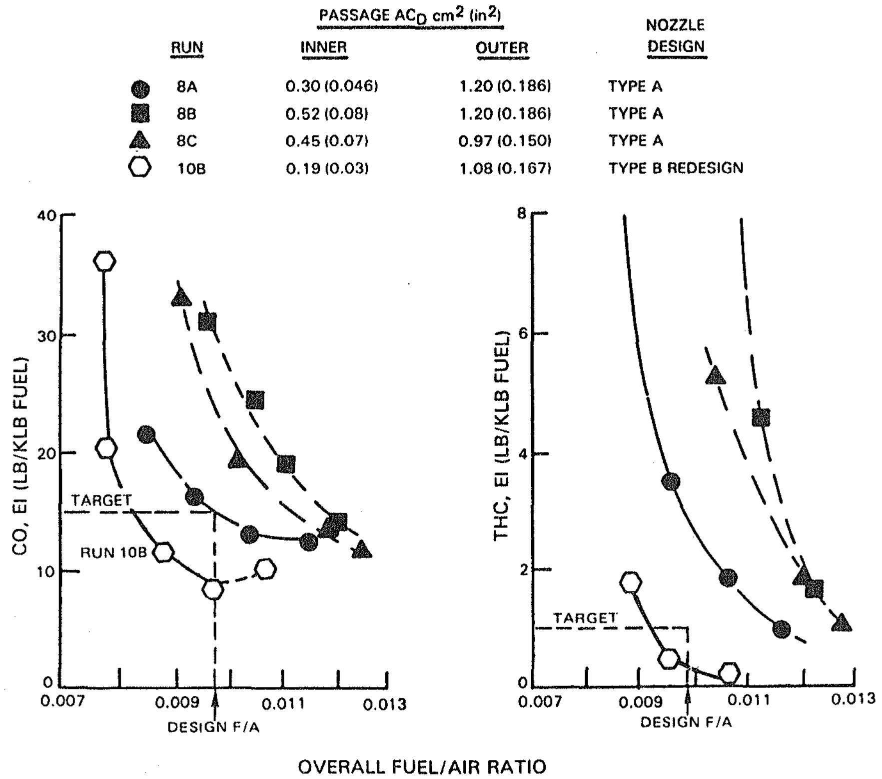


Figure 5.2.1-4 Idle Emissions with Redesigned Pilot Zone Fuel Injector (Type B)

5.2.1.2 Main Zone Optimization

Carburetor Tube Optimization

Several design variations of the main zone carburetor tube were evaluated during this part of the sector rig program with the intent of reducing high power oxides of nitrogen emissions and improving combustor performance. The different configurations are summarized in Table 5.2-I as Runs 7-8 and 10-11.

On the basis of results from the carburetor tube characterization tests, two approaches were evaluated for improving tube performance and its resultant effect on emissions and combustor performance. The first approach centered on increasing core airflow to enhance fuel/air preparation and lower the overall zone peak equivalence ratio. The core airflow was increased 20 and 10 percent, respectively, in configurations tested in runs 7 and 10 by installing increased height radial inflow swirlers. The results, as presented in Figure 5.2.1-5, indicate reductions of up to 20 percent were achieved in the level of oxides of nitrogen at climb power conditions for the higher core airflow rates.

In the second approach, swirl was introduced in the secondary air passage to provide more rapid mixing between secondary and core airflows. As shown previously in Figure 5.1.2-2, the external sleeve fingers in the baseline design were replaced with swirl generating inserts angled in the direction of the core airflow (co-rotating). These inserts resulted in a reduction in passage effective area because of the higher degree of blockage associated with swirling the flow. The 20-degree insert design, which necessitated a larger number of individual inserts relative to the 35-degree swirl configuration to ensure insert overlap, produced the greatest degree of blockage.

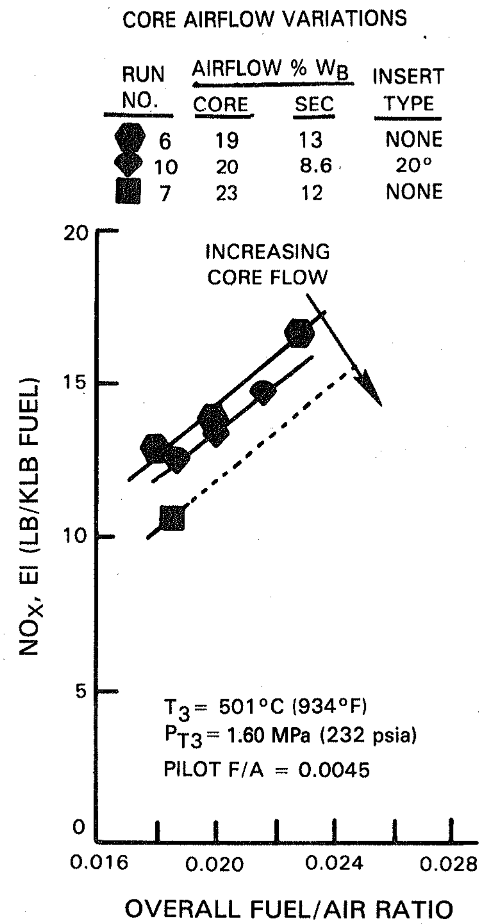


Figure 5.2.1-5 Impact of Increasing Carburetor Tube Core Airflow on High-Power Emissions

Swirl angles of 20 and 35 degrees were evaluated during test runs 8 and 11, respectively. The effects on high power oxides of nitrogen emissions are shown in Figure 5.2.1-6. Incorporating the 20-degree inserts in the secondary air passage contributed toward a significant reduction in oxides of nitrogen with no adverse impact on carbon monoxide and unburned hydrocarbon emissions levels. Increasing the angle to 35 degrees, however, failed to produce any additional reduction to the oxides of nitrogen level. Furthermore, it had a negative effect on carbon monoxide and unburned hydrocarbon levels at the approach condition. These results confirm that swirling the secondary air stream provides an improvement in mixing. The 20-degree inserts were selected as the prime configuration for the secondary air passage.

It should be noted that data from runs 8 and 11 were acquired with a second test rig having a new combustor section. This combustor, which was used only during these diagnostic evaluations for the purpose of test flexibility, had a slightly different pressure loss and resulting flowfield. In turn, this imparted changes to key combustor parameters. For example, when evaluating the effects of the 20- and 35-degree inserts in runs 8 and 11, core airflow also varied even though there was no change made to the tube geometry. Although these variations tended to mask the results, it is evident that increasing the core flow and providing a triggering action with the secondary flow produced significant reductions on oxides of nitrogen emissions.

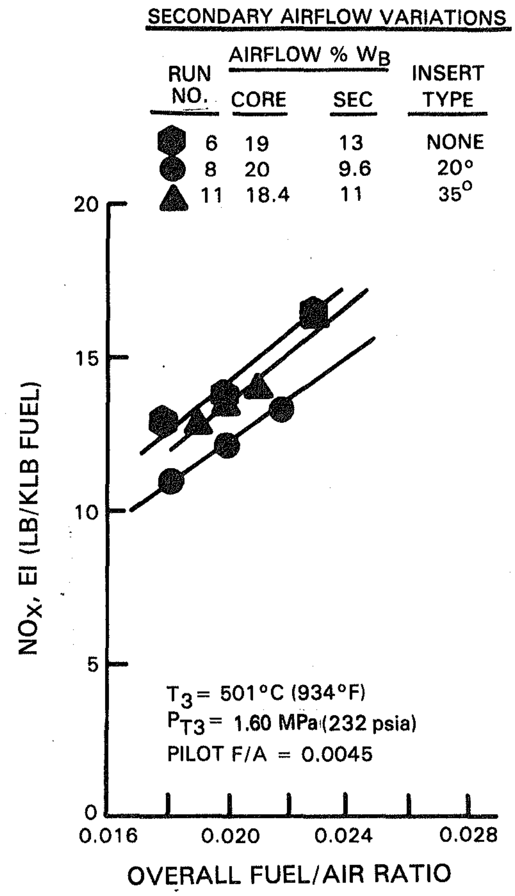


Figure 5.2.1-6 Effect of Swirl on High-Power Emissions

Fuel Staging Optimization

The capability to operate the combustor at high efficiency with both zones fueled at approach conditions was successfully demonstrated. This is an important accomplishment since a fueled main zone at approach enhances durability by reducing pilot zone temperatures and minimizes the possibility of main zone fuel nozzle coking. In addition, a fueled main zone is desirable in terms of engine response time during snap accelerations. In specific, the time required for filling an empty manifold results in a longer engine acceleration time.

Efficient fuel staging was achieved by minimizing the amount of dilution air in close proximity to the carburetor tube injection plane and operating with a small percentage of fuel supplied to the main zone (15 percent of total). Achieving efficient staging at low main zone fuel flows produced two beneficial effects in terms of combustor stability and exhaust emissions. First, the resulting highly fueled pilot operates at the high peak zone equivalence ratios required for high combustion efficiency and improved stability during transient engine operation. Second, the main zone contribution to overall combustor emissions, which is proportional to the percent of main zone fuel flow, was reduced.

The benefit of operating at low percentages of main zone fuel flow can be observed from the results of parametric testing conducted at the approach condition shown in Figure 5.2.1-7. During the test, the percentage of main zone fuel flow was varied by increasing main zone fuel flow at fixed pilot conditions and by decreasing pilot fuel flow at fixed main zone conditions. As shown in both cases, carbon monoxide emissions responded favorably to decreased percentages of main zone fuel flow.

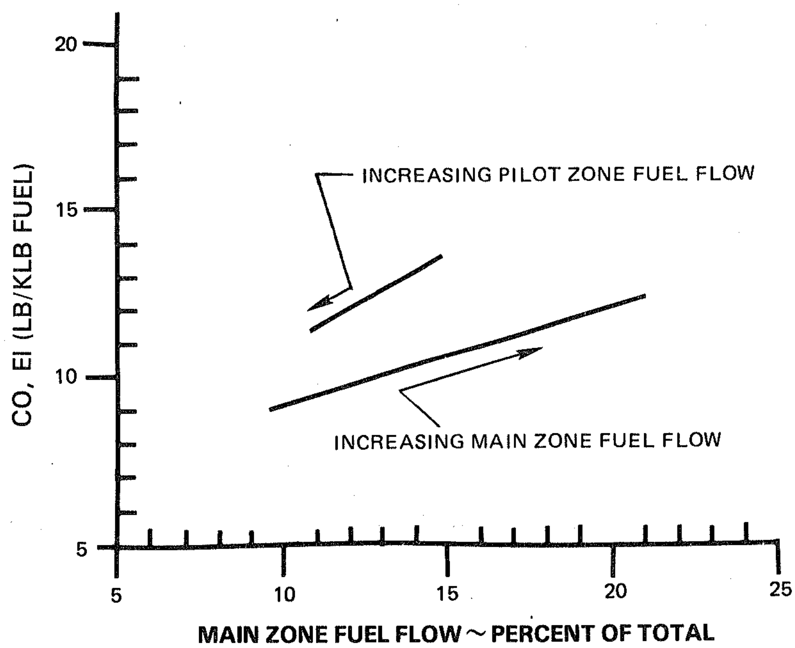


Figure 5.2.1-7 Carbon Monoxide Emissions Versus Main Zone Fuel Flow at Approach

The ability to operate the main zone efficiently at low fuel flows demonstrates that the carburetor tube injection system benefits not only high power operation but also provides a workable injection system at low power conditions. The system, as discussed previously, eliminates the dependency on fuel pressure drop to atomize fuel in the main combustor zone. This was confirmed during cold flow visualization testing when no deterioration in fuel spray quality was observed even at lower fuel flows.

5.2.1.3 Combustor Aerodynamic Sensitivity Tests

Pratt & Whitney Aircraft's combustor development experience has shown that variations in the aerodynamic flow field entering the combustor can affect both performance and emissions levels. To demonstrate tolerance or insensitivity to aerodynamic type disturbances, two combustor configurations were evaluated during test runs 14 and 16.

Sensitivity to prediffuser inlet total pressure profile perturbations was evaluated during run 14 using the combustor configuration from run 11 with longitudinal screening installed upstream of the prediffuser section to shift the radial pressure profile peak from 50 to 65 percent span. Thus, configurations 11 and 14 were identical except for the inlet flow profile variations. Results from the Diffuser/Combustor Model Test Program were used to size and locate the adjustment.

The results of the test are presented in Table 5.2.1-I by the performance and emissions characteristics of configurations 11 and 14. As shown, all parameters remained essentially unchanged, thereby exhibiting essentially no dependence on inlet total pressure profile.

TABLE 5.2.1-I
COMBUSTOR AERODYNAMIC SENSITIVITY INVESTIGATION
(Configurations 11 and 14)

	11	14
Emissions*		
Carbon Monoxide	2.09	2.33
Unburned Hydrocarbons	0.69	0.57
Oxides of Nitrogen	5.09	5.10
Pattern Factor	0.24	0.23
Lean Blowout Fuel/Air Ratio	0.0047	0.0045

* Environmental Protection Agency Parameter

The performance and emissions sensitivity to hood inlet capture area and radial position was determined in test run 16. The combustor configuration was almost identical to the configuration in test run 10, with the exception of a 25-percent reduction in the hood capture area. This reduction was obtained by closing down the inner diameter side of the hood inlet ports.

The effects are shown in Table 5.2.1-II. The results indicate that the decrease in hood capture area caused a shift in liner pressure loss between the outer and inner liners. This suggests that a redistribution in combustor airflow occurred with a higher percentage of air entering through the outer liner and carburetor tubes. The most notable effect on emissions occurred at the approach condition, in which carbon monoxide and unburned hydrocarbon levels increased approximately 100 percent. This increase was most likely the result of the previously mentioned higher carburetor tube airflows, which produced a low equivalence ratio at the approach condition. Overall, the modification had very little impact on either performance or emissions goals.

TABLE 5.2.1-II
COMBUSTOR AERODYNAMIC SENSITIVITY EVALUATION
(Test Run 10 and 16)

	10	16
Pressure Loss (%)		
Section	5.37	5.02
Outer Liner	2.34	2.22
Inner Liner	3.05	2.32
Emissions Index at Approach		
Carbon Monoxide	7.5	16.5
Unburned Hydrocarbons	4.2	8.2

5.2.1.4 Environmental Protection Agency (EPA) Parameters and Society of Automotive Engineers (SAE) Smoke Numbers

Table 5.2.1-III presents the emissions Environmental Protection Agency Parameters and Society of Automotive Engineers smoke numbers for the configurations in which sufficient test data were acquired. The Environmental Protection Agency Parameters include margins for development and variability as established from production engine experience with low emissions combustors. These parameters were not calculated for configurations 12 and 13, which were evaluated for altitude relight, nor for the first four configurations, because of the inability to achieve a stable operating condition at approach.

As indicated in Table 5.2.1-III, the best overall emissions levels were achieved with configuration 10B. Carbon monoxide and total unburned hydrocarbon levels were appreciably lower than the established goals. However, oxides of nitrogen emissions exceeded the goal. It is noteworthy to point out that the level of oxides of nitrogen is lower than that extrapolated from the previous Experimental Clean Combustor Program (Ref. 2), indicating that technical progress is being made. Smoke levels were well below the goal. On the basis of these results, the emissions reduction features in the 10B configuration were used in establishing the final design of the Energy Efficient Engine combustor component.

TABLE 5.2.1-III
EMISSIONS SUMMARY WITH LOUVERED LINER SECTOR COMBUSTOR RIG
(Environmental Protection Agency Parameters* and Smoke Numbers**)

	Carbon Monoxide	Unburned Hydrocarbons	Oxides of Nitrogen	Smoke
Goal	3.00	0.40	3.00	20
Run 5	3.28	0.96	4.54	1
Run 6	3.40	0.85	4.81	1
Run 8	2.90	0.54	5.00	1
Run 9	2.52	0.24	4.95	4
Run 10A	2.00	0.36	4.88	1
Run 10B	2.07	0.26	4.65	1
Run 11	2.09	0.69	5.09	1
Run 14(1)	2.33	0.57	5.10	1
Run 15(1)	2.37	0.65	(2)	1
Run 16(1)	2.20	0.45	4.60	1

* Environmental Protection Agency Parameter (pound pollutant/1000 pounds-thrust hour/cycle)
**Society of Automotive Engineers Smoke Number
(1) Combustor aerodynamic sensitivity evaluations
(2) Oxides of nitrogen instrumentation failure

5.2.2 Performance Characteristics

The Energy Efficient Engine combustor configuration demonstrated the capability to meet or exceed all aerothermal performance goals, while maintaining emissions control. In the following sections, combustor performance is discussed in terms of ignition and stability, pressure loss and exit temperature distribution.

5.2.2.1 Combustion Ignition and Stability

Table 5.2.2-I summarizes the idle lean blowout (LBO) characteristics demonstrated during rig testing. The early configurations, which exhibited high levels of carbon monoxide and unburned hydrocarbons at idle, generally experienced blowout in the fuel/air ratio range of 0.006 to 0.008. However, levels as low as 0.003 were achieved with later configurations, which also exhibited very low carbon monoxide and hydrocarbon emissions.

TABLE 5.2.2-I
STABILITY SUMMARY

Run Config.	Lean Blowout Limit	Run Config.	Lean Blowout Limit
Shakedown	0.0068	8	0.0064
2	0.0060	9	0.0059
3	0.0083	10A	0.0061
4	0.0080	10B	0.0066
5	0.0061	11	0.0047
6	0.0057	14	0.0045
7	0.0030	15	0.0068
		16	0.0058

Altitude relight and sea level start characteristics were evaluated with the configuration used in run 10 and two candidate pilot injector designs (Types A and B). Testing was conducted with combustor inlet conditions representative of compressor windmilling over the Energy Efficient Engine flight envelope. Fuel flow was varied at each condition to ascertain the minimum required flow for ignition.

The altitude relight results with Types A and B (redesigned) injectors are shown in Figures 5.2.2-1 and -2. The results show that ignition was achieved with both designs over the range of conditions representative of the flight envelope. Furthermore, ignition was demonstrated at an altitude of 10,668 m (35,000 ft) with fuel flows as low as 21 kg/hr (48 lb/hr), both of which exceed requirements.

Although both injectors demonstrated similar altitude relight capabilities, sea level start requirements could only be satisfied with the Type B injector. As shown in Figure 5.2.2-3, ignition with this injector was achieved at flows of 87 kg/hr (192 lb/hr) and above, surpassing the Energy Efficient Engine requirements of ignition within 30 seconds at fuel flow no greater than 190 kg/sec (420 lb/sec).

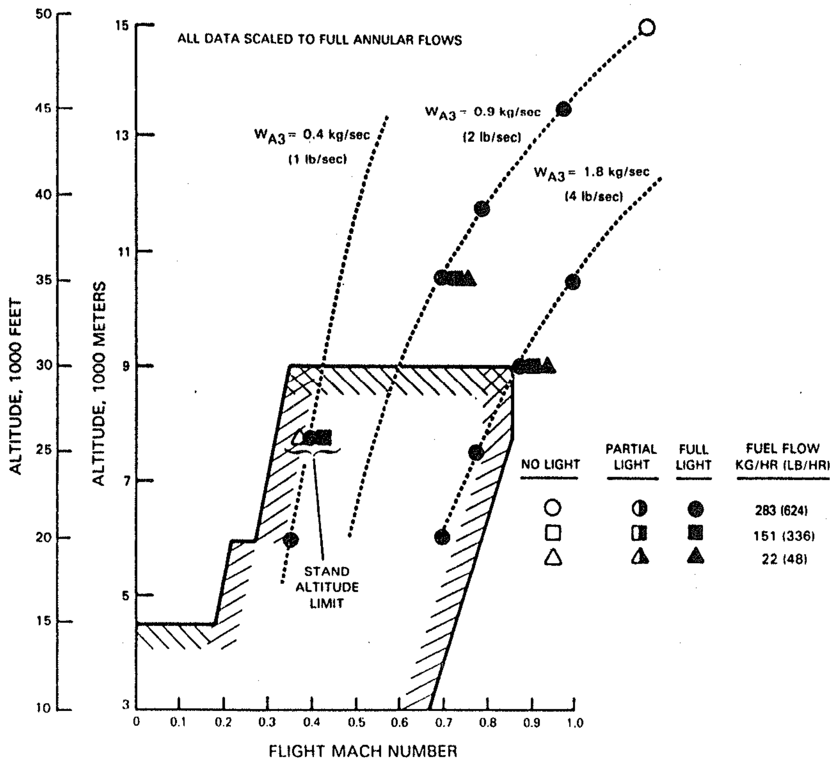


Figure 5.2.2-1 Altitude Relight Results with Type B (Redesigned) Fuel Injector

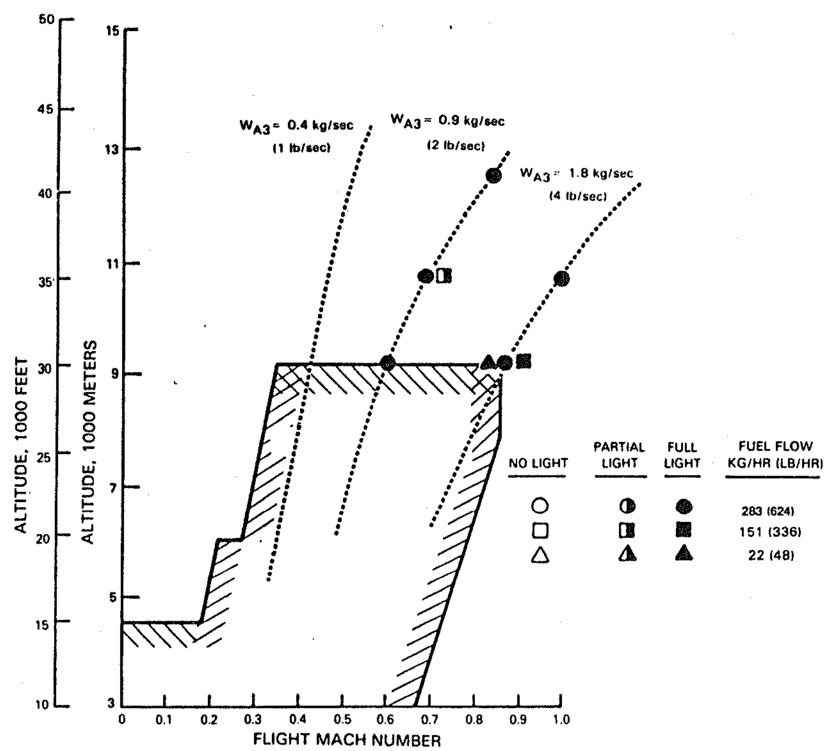


Figure 5.2.2-2 Altitude Relight Test Results with Type A Fuel Injector

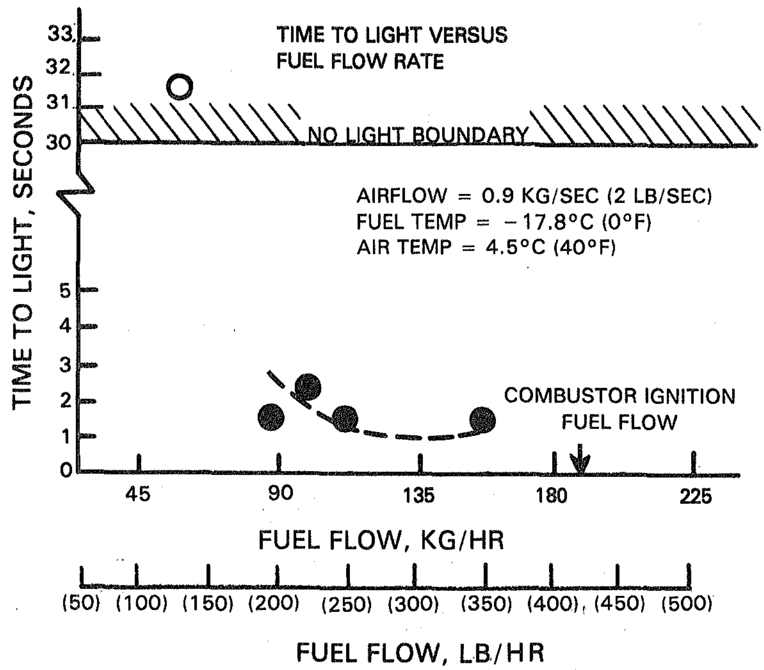


Figure 5.2.2-3 Sea Level Ignition Results with Type B (Redesigned) Fuel Injector

Altitude relight and sea level ignition characteristics also were evaluated while operating with two different test fuels (ERBS 1 and ERBS 2), as part of the NASA-sponsored Broad Specifications Fuel Program (Ref. 3). At the design starting fuel flow, ignition times were essentially equal to those when operating with Jet A fuel. However, an interesting result was that at reduced fuel flows ignition times increased with fuels having a lower hydrogen content. The results in Figure 5.2.2-4 show that ignition times with Jet-A fuel were not affected by a decrease in fuel flows, while ignition times with both test fuels increased significantly. The complete results of this investigation under the Broad Specification Fuel Program will be published in a future NASA Contractor Report.

5.2.2.2 Pressure Loss

The goal established for overall system pressure loss (combustor inlet to exit) is 5.5 percent of the station 3 (high pressure compressor exit location) total pressure. In addition, the inner and outer liners are designed for a loss of 2.5 percent of the station 3 total pressure to provide adequate turbine cooling supply pressure.

A summary of combustor pressure loss characteristics is contained in Table 5.2.2-II. The initial configurations demonstrated outer liner pressure losses that were below the goal. The configuration tested in run 4 had a lower combustor liner effective flow area to increase pressure loss to the goal level. Subsequent testing was conducted with approximately the same area.

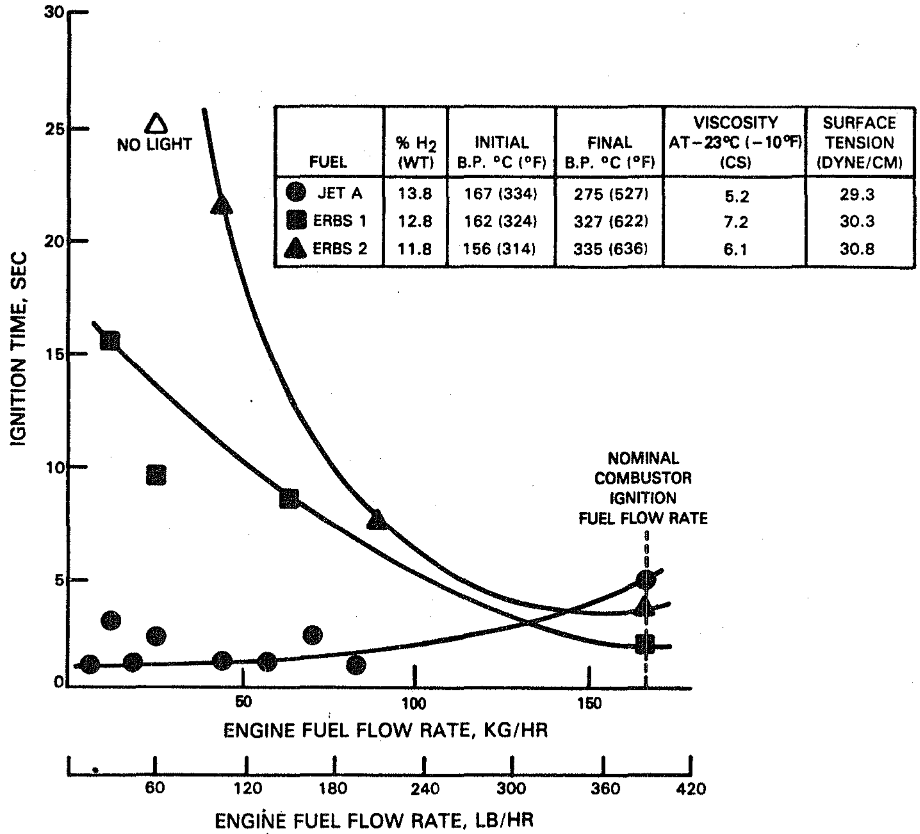


Figure 5.2.2-4 Ignition Time Versus Fuel Flow Rate for Jet-A, ERBS 1 and ERBS 2 Fuel Types (Broad specification fuel program data)

TABLE 5.2.2-II
SUMMARY OF COMBUSTOR PRESSURE LOSS CHARACTERISTICS

	Overall* Loss (%)	Outer Liner** Loss (%)	Inner Liner** Loss (%)
Goal	5.50	2.50	2.50
Run 1	4.45	1.75	2.20
Run 2	4.80	2.10	2.60
Run 3	4.85	2.18	2.62
Run 4	5.44	2.71	3.26
Run 5	5.46	2.71	3.30
Run 6	5.03	2.35	2.83
Run 7	5.15	2.51	2.91
Run 8	5.94	2.94	3.58
Run 9	5.38	2.38	3.03
Run 10	5.37	2.34	3.05
Run 11	5.45	2.56	2.99
Run 14	5.46	2.46	3.10
Run 15	5.26	2.44	2.72
Run 16	5.02	2.23	2.32

* Station 3 to 4
** Station 3.9 to 4

Pressure loss across the inner liner was generally 0.5 percent greater than that across the outer liner. This agreed with results observed during the preceding Diffuser/Combustor Model Test Program. The two liner losses became nearly equal with the configuration evaluated during test run 16, which had a decrease in hood capture area of approximately 25 percent. The inner biased blockage produced a shift in combustor airflow distribution, with a higher percentage entering through the outer liner, when reduced overall pressure loss slightly.

5.2.2.3 Exit Temperature Distribution

Pattern Factor

Combustor pattern factor was measured at high power conditions, usually with a pilot fuel/air ratio of 0.003. This setting corresponds to the optimum fuel split for low oxides of nitrogen emissions at high power conditions.

A summary of the pattern factors is presented in Table 5.2.2-III. In comparison to the goal of 0.37, pattern factors generally ranged between 0.15 and 0.28. These low levels provide the confidence that the goal will be met during the Combustor Component Rig Test Program.

TABLE 5.2.2-III
COMBUSTOR PATTERN FACTOR SUMMARY

Configuration	Pattern Factor
Goal	0.37(max)
Shakedown	Not Applicable
Run 2	0.28
Run 3	0.30
Run 4	0.18
Run 5	0.17
Run 6	0.18
Run 7	0.28
Run 8	0.17
Run 9	0.26
Run 10	0.15
Run 11	0.24
Run 14	0.23
Run 15	0.16
Run 16	0.18

The circumferential temperature profile shown in Figure 5.2.2-5 for configuration 10 is typical for most of the later configurations. This profile shows that temperature patterns are not influenced adversely by strut wakes or fuel injector positions. These data indicate the absence of strut wakes and confirm the diffuser/combustor model test results.

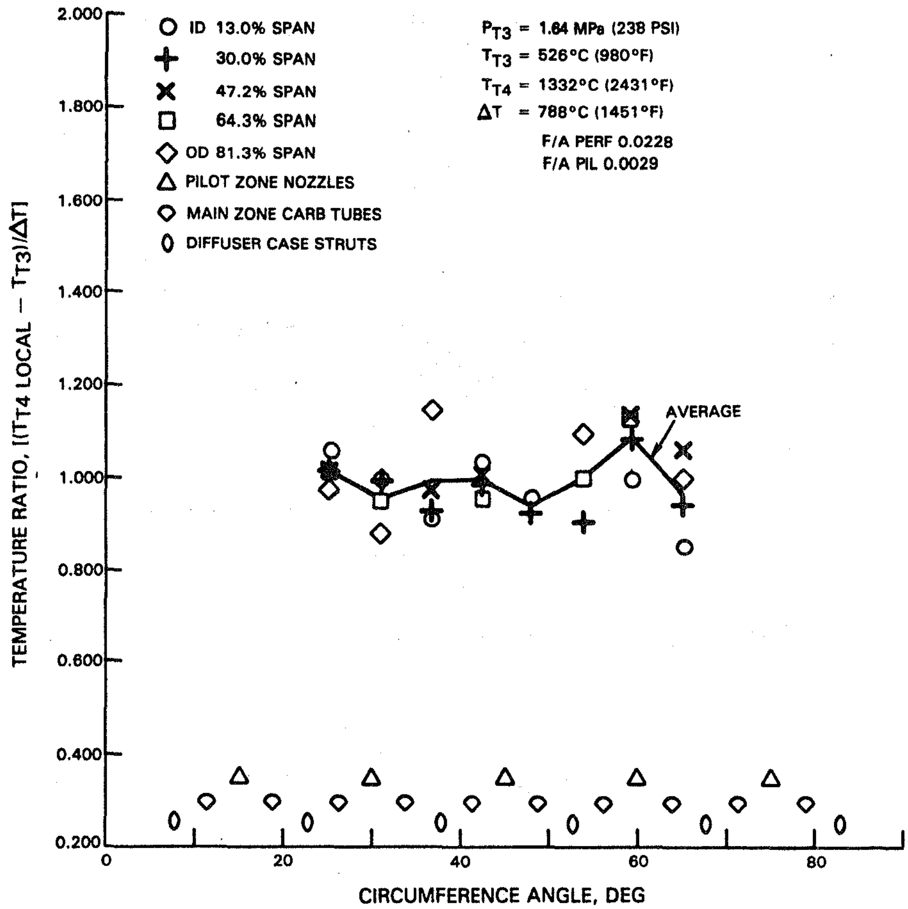


Figure 5.2.2-5 Typical Exit Circumferential Temperature Profile Showing Negligible Impact of Upstream Struts on Fuel Injectors

The most notable improvement in pattern factor was produced by installing swirl generating inserts into the carburetor tube secondary air passages (configuration 8). This modification, incorporated to reduce high power oxides of nitrogen emissions, lowered the pattern factor from 0.28 to 0.17. This resulted from the improved fuel/air mixing provided by swirling the secondary air stream.

Shifts in pattern factor also occurred from changes in exit temperature radial profile. These shifts were primarily the results of reductions in cooling levels in the rearmost louvers and/or changes in dilution hole sizes and locations. Typically, configurations with more peaked profiles generally produced higher pattern factors. Since these shifts in pattern factor were related to radial temperature patterns rather than circumferential type disturbances, they were addressed by radial profile tailoring techniques.

Exit Temperature Radial Profile

Modifications for tailoring exit temperature radial profile principally involved varying the size and location of main zone dilution holes and were usually evaluated along with other modifications aimed at reducing emissions. The trends in Figure 5.2.2-6 show the effectiveness of dilution air management in tailoring exit temperature profiles. The different main zone dilution schedules for each configuration are listed in Table 5.2.2-IV.

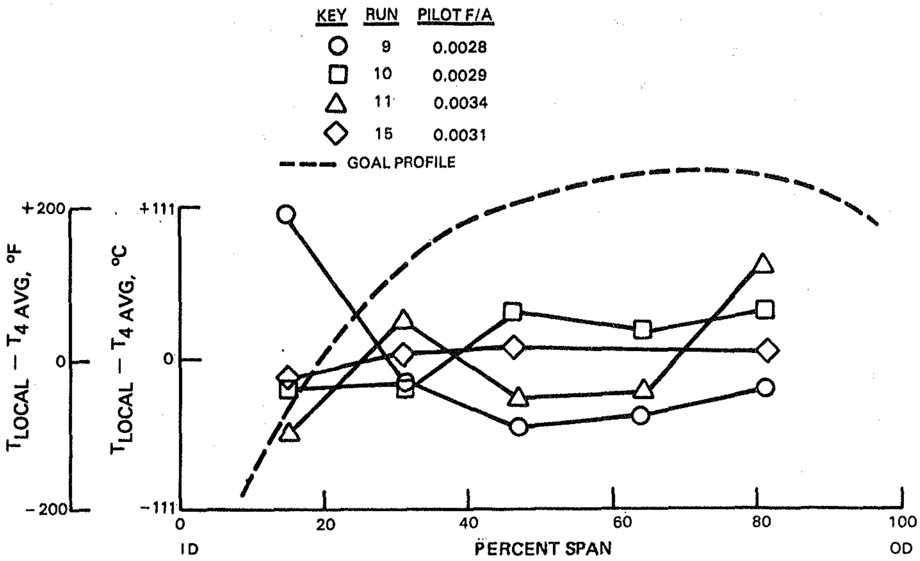
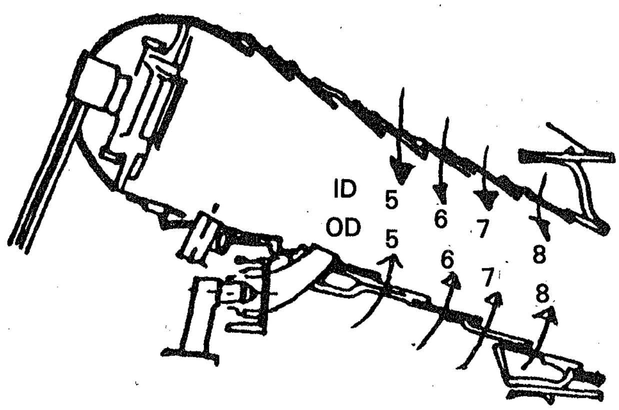


Figure 5.2.2-6 Comparison of High Power Exit Temperature Radial Profiles

TABLE 5.2.2-IV
MAIN ZONE DILUTION AIR
(Percent of Combustor Flow)



	Inner Liner				Outer Liner			
	Row 5	Row 6	Row 7	Row 8	Row 5	Row 6	Row 7	Row 8
Run 9	2.7	13.9	0	0	0	6.1	0	0
Run 10	0	11.0	1.2	1.2	0	6.0	0	1.0
Run 11	0	7.1	2.4	0	4.3	0	2.3	0
Run 15	3.3	1.3	1.2	0	5.1	1.1	1.1	0

The results show that the configuration used in run 9 exceeded the goal profile by approximately 148°C (300°F) near the inner wall. This condition was successfully resolved in the following test (run 10) by installing a large number of small holes 0.317-cm (0.125-in) diameter in the rearmost inner panels. Small holes were employed to minimize jet penetration.

Similar effects of dilution air management on exit temperature radial profile are apparent by comparing the profiles obtained with the configurations tested in runs 11 and 15. In general, it can be stated that the overall shape of the exit profile is set by the carburetor tube airflow characteristics and large diameter dilution holes. Furthermore, exit temperatures near the outer and inner walls can be trimmed, in effect, by a large number of small holes (for example, 0.317-cm (0.125-in) diameter) located in the rearmost panels. This technique for tailoring radial profile will be used during the Combustor Component Rig Test Program.

5.2.3 Safety Characteristics

The main zone carburetor tube design features a degree of premixing of fuel and air prior to injection into the main combustion zone. Carburetor tube size and airflow distribution were carefully selected on the basis of available auto-ignition characteristic data to preclude any possibility of flashback or auto-ignition. Observations made after each test revealed no evidence of combustion within the carburetor tube.

5.2.4 Mechanical Performance

During all tests, temperatures recorded on the louvered liners were consistently low and well within acceptable limits using the design cooling flow level of 33 percent of combustor airflow (Figure 3.4.2-2). Post-test inspection confirmed the low temperature levels, showing no apparent signs of thermal distress such as incipient cracking and buckling. The typical post-test condition of the liner is shown in Figure 5.2.2-7.

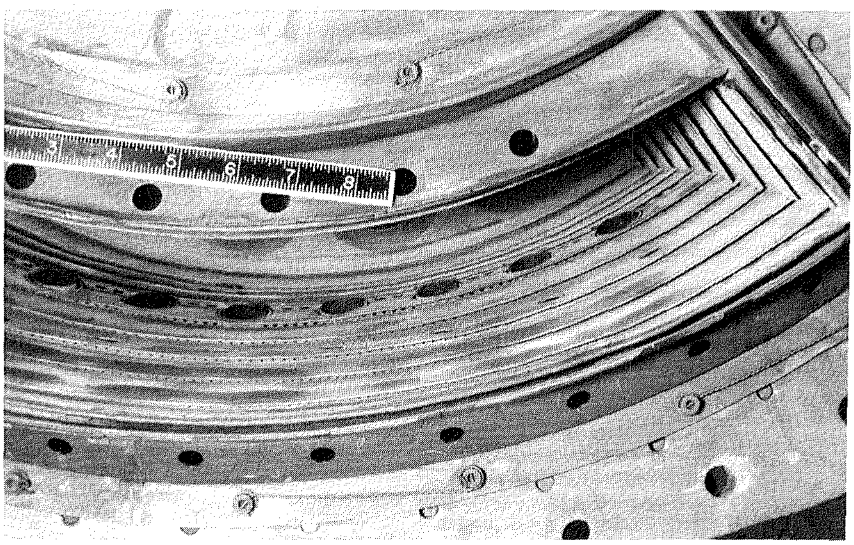


Figure 5.2.2-7 Typical Post-Test Condition of the Sector Rig Louver Liner Configuration

Although some coking in the carburetor tubes was observed with the initial configurations, coke deposits overall were minimal. Coking was the result of inefficient operation of the main zone at the approach condition. This problem was eliminated when efficient operation was achieved.

5.2.5 Performance and Emissions Test Summary

In summary, this first phase of the of the sector combustor rig test program was successful in refining the Energy Efficient Engine combustor design. All performance and emissions goals, with the exception of oxides of nitrogen, were achieved. A pilot zone airflow schedule and a fuel nozzle design were established that produced significant reductions in carbon monoxide and unburned hydrocarbons at low power conditions. The main zone carburetor tube design was optimized to reduce oxides of nitrogen at high power conditions as well as improve the exit temperature pattern factor. Finally, ignition and stability characteristics of both the pilot and main combustion zones were successfully demonstrated.

5.3 ADVANCED SEGMENTED LINER TESTS

Testing in the second phase of the program was directed towards evaluating the structural integrity of the segmented liner design with the advanced counter-parallel FINWALL® cooling scheme. A series of four tests was conducted using the configurations summarized in Table 5.3-I. The results of these tests are discussed in the following sections. A description of the test configurations is contained in Appendix B and a test data summary sheet for each configuration is contained in Appendix C.

5.3.1 Emissions and Performance Tests

The configuration evaluated in the initial test of the advanced liner (run 18) featured a pilot zone and dilution air schedule similar to run configuration 10B. Because of fabrication lead times, the carburetor tubes in this configuration were similar to those used in earlier tests with the louvered liner (1.2 cm (0.5 in) radial inflow swirlers and nonswirling secondary air). The outer diameter carburetor tube scoop (Figure 5.1.1-1) was purposely not included to evaluate the potential for design simplification.

Testing was conducted over the full range of operating conditions for the Energy Efficient Engine at pressures up to 30,343,360 Pa (440 psia). As shown in Figure 5.3.1-1, emissions characteristics were essentially the same as those demonstrated with the best louvered liner configuration. All emissions and smoke goals were achieved except for oxides of nitrogen, which remained approximately 50 percent above the design goal.

The exit temperature radial profile was similar to the louvered liner configuration, as shown in Figure 5.3.1-2. The only notable deviation is the cooler region near the outer wall. The exit temperature pattern factor increased to 0.35. This is attributed to the use of nonswirling secondary airflow carburetor tubes. For the configuration used during run 19, the carburetor tubes were modified to include secondary air swirl and a scoop was added to the outer liner support frame to improve the air feed to the carburetor tubes. This reduced the pattern factor to 0.26, which is well below the goal of 0.37 and consistent with results from previous louvered liner tests.

TABLE 5.3-I
SUMMARY OF ADVANCED SEGMENTED LINER SECTOR RIG CONFIGURATIONS

Test Run No	Type	Purpose/Configuration
18	Emissions/Performance	Initial test with segmented liner: o Run 10 airflow schedule o Redesigned pilot injectors o Baseline carburetor tubes (nonswirling secondary airstream)
19	Thermal-Mechanical	Changes relative to Run 18: o Tube immersion increased to 0.7 cm (0.3 in) o 20-degree swirler inserts installed in carburetor tube secondary passages o Outer shroud scoop added to improve carburetor tube feed o Feather seal lengths increased at liner segment edges
20	Thermal-Mechanical	Changes relative to Run 19: o Tube immersion decreased 0.38 cm (0.15 in) o Row 1 outer liner dilution air eliminated o Local feather seal cooling added in three areas
21	Emissions/Performance	Changes relative to Run 20: o Relocated center three pilot injectors outboard 0.476 cm (0.187 in)

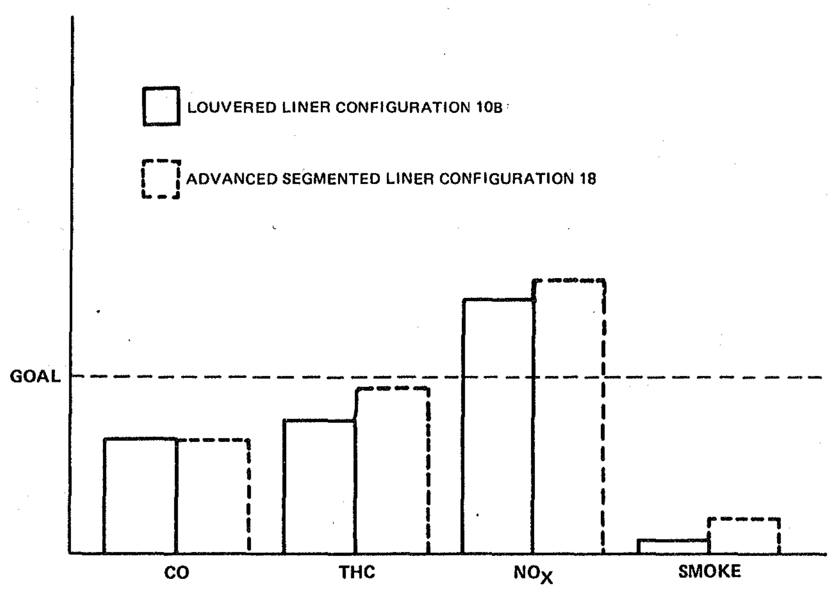


Figure 5.3.1-1 Comparison of Emissions Levels with Louvered and Segmented Liners

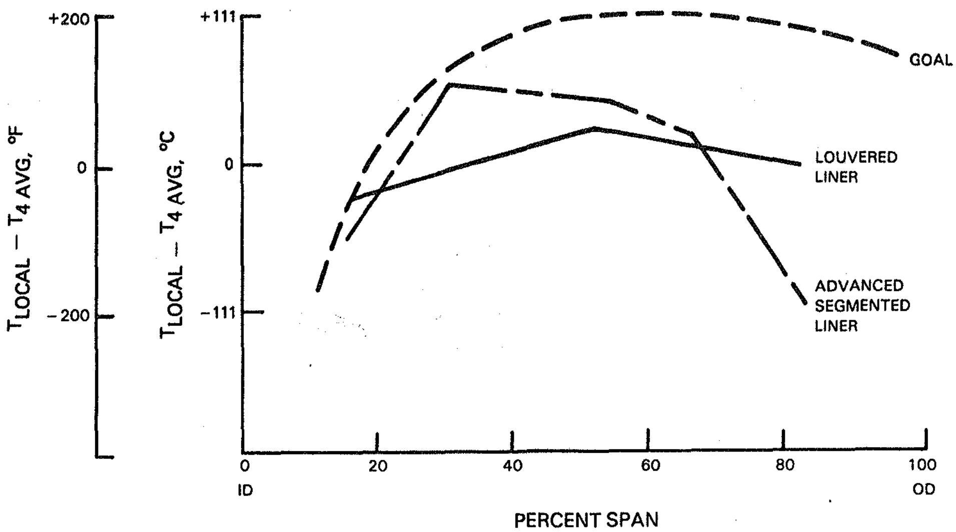


Figure 5.3.1-2 Comparison of Exit Temperature Profiles with Louvered and Segmented Liners

Performance and emissions characteristics of the configuration for runs 20 and 21 are presented in Table 5.3.1-I. These results show attainment of virtually all goals. The emissions parameters again include margins for variability and development (see Figure 5.2.1-4).

TABLE 5.3.1-I
ADVANCED SEGMENTED LINER PERFORMANCE AND EMISSIONS
(Configuration for Runs 20 and 21)

	Goal	Configurations 20 and 21
PRESSURE LOSS (Percent P_{t3})		
Section	5.5	5.22
Outer Liner	2.5	2.41
Inner Liner	2.5	2.70
EMISSIONS		
Carbon Monoxide	3.0	2.30
Unburned Hydrocarbons	0.4	0.38
Oxides of Nitrogen	3.0	4.70 (est.)
Smoke Number	20	4
Pattern Factor:	0.37 (max)	0.26
Radial Profile : Refer to Figure 5.3.1-2		

The combustor airflow distribution for the advanced liner configuration used in test runs 20 and 21 is shown in Figure 5.3.1-3. As shown, all of the pilot zone and the majority of main zone combustion air is supplied in close proximity to the respective fuel source. Liner cooling is above the desired level because of two factors. The first is excess leakage, which accounts for 3 percent of the combustor airflow. The second is the higher than anticipated inner liner pressure loss, which increased cooling by approximately 2 percent of the combustor airflow. However, no deleterious affect could be discovered from the excessive cooling, and it is anticipated that the level will be reduced by closing off areas in the overcooled region during the combustor component test program.

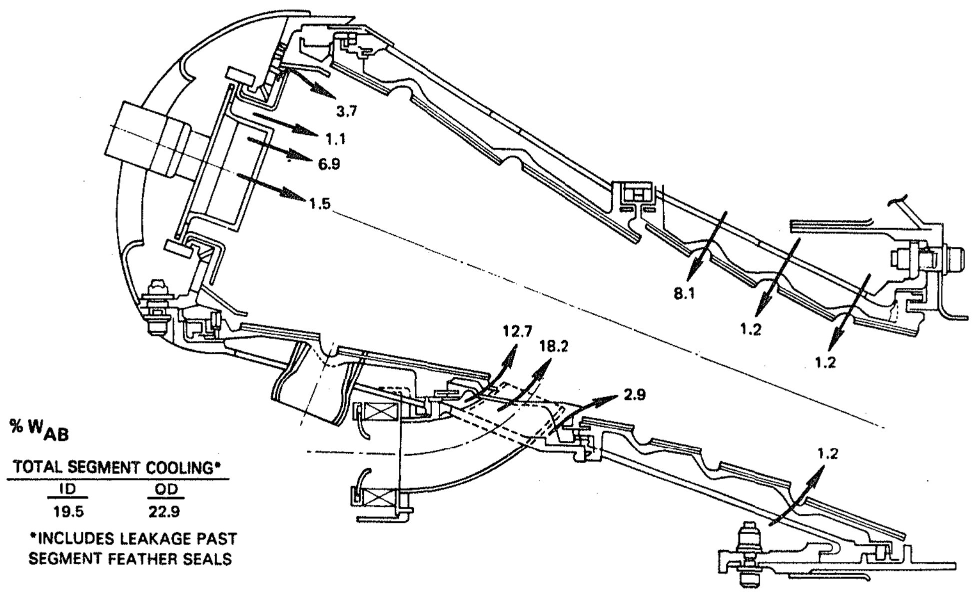


Figure 5.3.1-3 Advanced Segmented Liner Airflow Distribution for Runs 20 and 21

The final advanced liner test (configuration 21) was conducted as part of the Broad Specification Fuel Program. The combustor was evaluated over the full range of operating conditions with Jet A fuel and two additional test fuels (ERBS 1 and ERBS 2) with progressively higher aromatic content. In general, test results indicated that low power emissions exhibited very little dependency on aromatic content, while high power oxides of nitrogen emissions increased with increasing aromatic content. These results are consistent with trends observed in previous tests with a conventional single-stage combustor.

It should be emphasized that although differences existed in the cooling characteristics of the advanced segmented liner and conventional louvered liner designs, comparable emissions and performance were achieved with both designs.

5.3.2 Thermal-Mechanical Performance Evaluation

The thermal-mechanical performance of the segmented liner was evaluated at representative engine operating conditions. Temperature sensitive paint and imbedded thermocouples were used to measure segment wall temperatures and gradients during each of the four evaluations.

Testing with the initial advanced segmented liner configuration (run 18) showed hot streaks approaching 1010°C (1850°F) on the last panel of the outer rear segments. The hot streaks were localized predominantly downstream of the carburetor tubes and accompanied by evidence of fuel staining. The temperature patterns are depicted in Figure 5.3.2-1, and the post-test condition of the liner is shown in Figure 5.3.2-2.

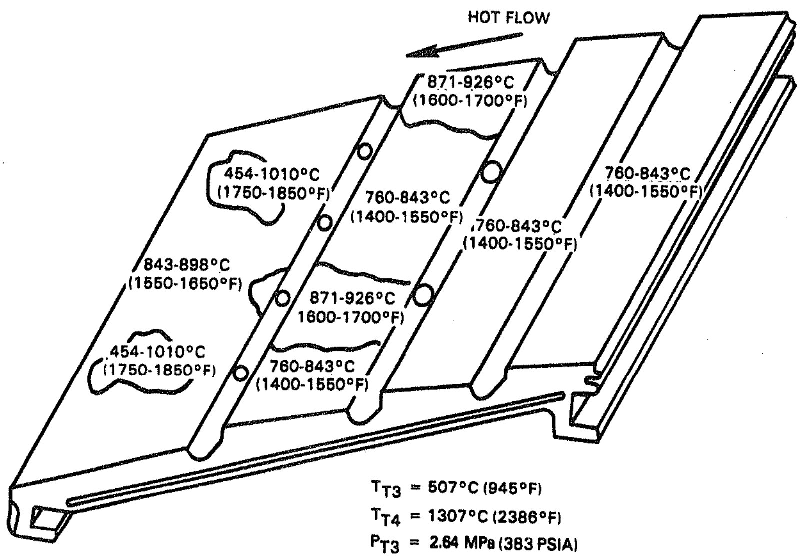


Figure 5.3.2-1 Rear Outer Liner Segment with Typical Post-Test Temperature Patterns Identified. Run 18

Since the fuel staining occurred downstream of the carburetor tubes, the tube immersion depth and the quality of carburetor tube air feed (absence of scoop) were suspected as the origin of this condition. For the following test (run 19), several carburetor tube modifications were incorporated. These consisted of: (1) an increase in tube immersion to 0.7 cm (0.3 in), (2) 20-degree swirler inserts in the secondary air passages, and (3) an outer scoop to improve air feed to the secondary air passages. In addition, the length of all axial feather seals was increased approximately 0.63 cm (0.25 in) to reduce leakage between segments.

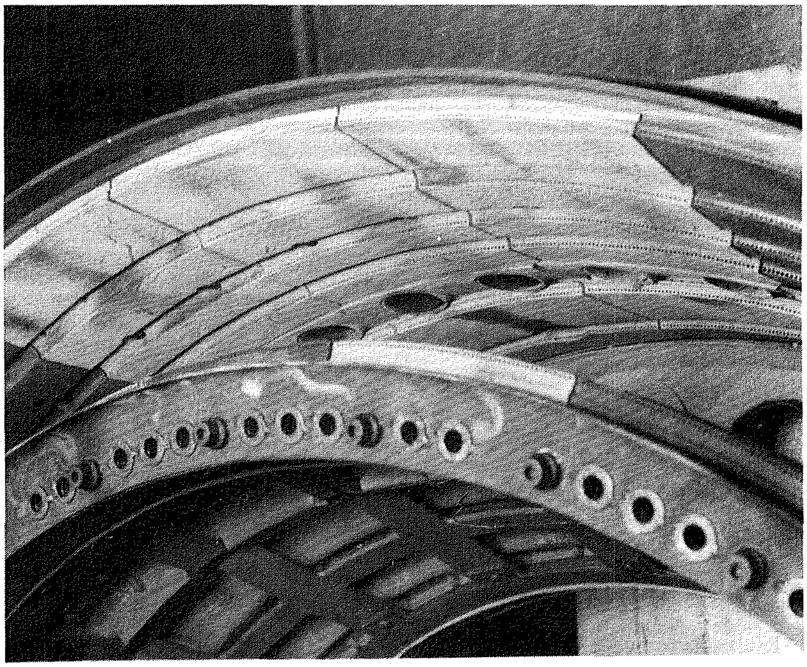


Figure 5.3.2-2 Post-Test Condition of Segmented Liner After 15.5 Hot Hours of Testing

These revisions were successful in reducing the outer diameter rear segment maximum temperature by approximately 93°C (200°F) (adjusted to liner design conditions) and they also eliminated fuel staining. However, the hot streak intensity increased on the inner rear segment directly opposite the carburetor tubes. This condition is shown in Figure 5.3.2-3. Figure 5.3.2-4 presents a comparison of typical temperature patterns on the inner segments for test runs 18 and 19. As indicated, temperatures on the panel edges along the axial feather seals were in excess of 1093°C (2000°F). Most other liner temperatures were either at or below predicted levels.

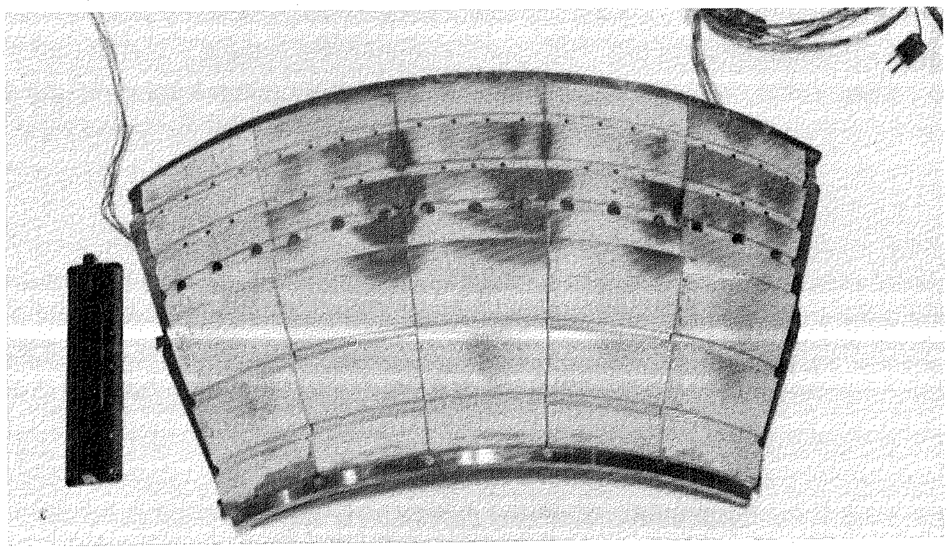


Figure 5.3.2-3 Post-Test Condition of Inner Liner with Thermal Sensitive Paint After Completion of 20 Minutes at Maximum Temperature (Run 19)

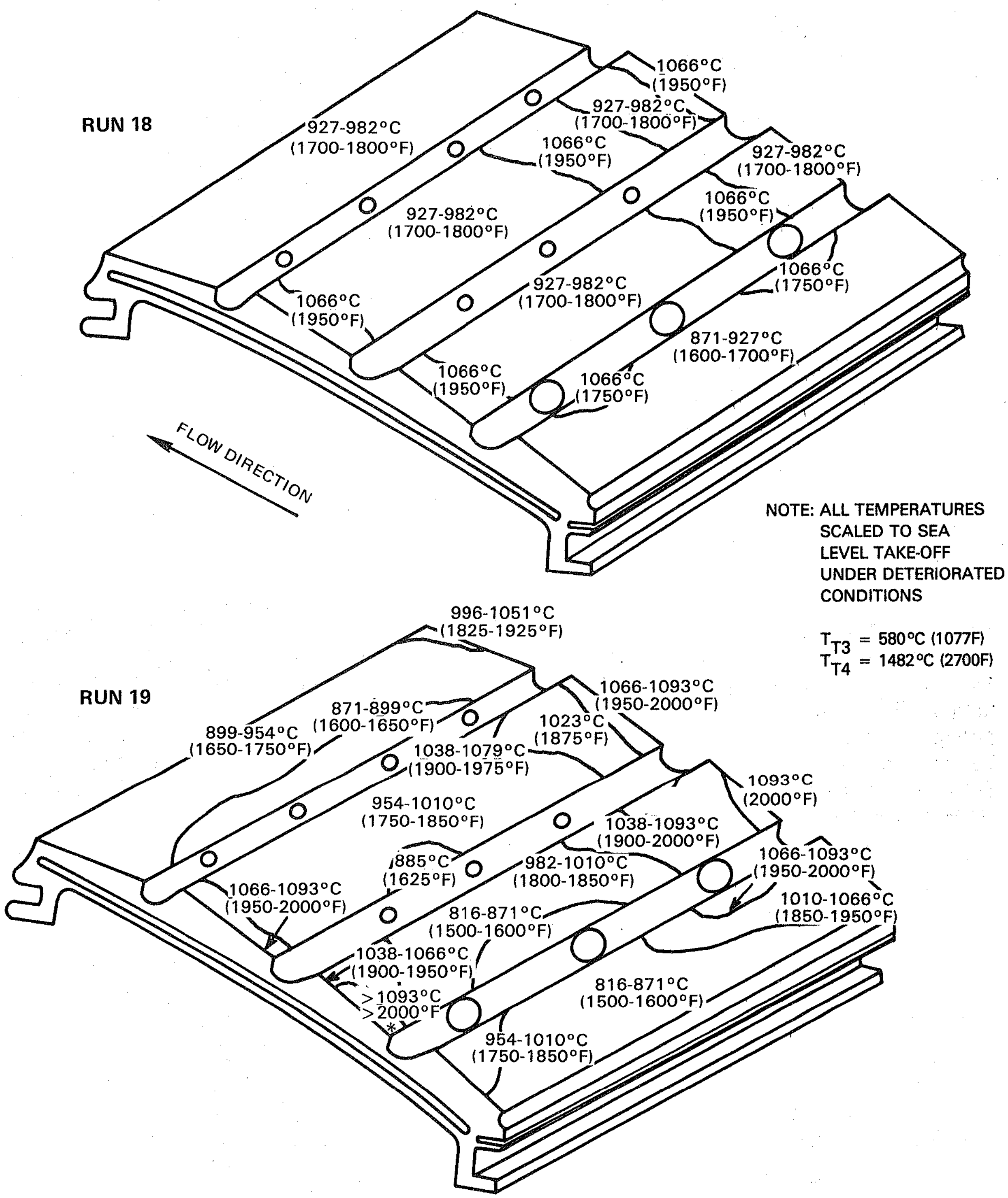


Figure 5.3.2.4 Comparison of Runs 18 and 19 Thermal Paint Results for Inner Rear Panels

The third test (run 20) focused specifically on reducing the streak temperatures in the inner rear segments. Carburetor tube immersion was reduced 0.38 cm (0.15 in) and the first row of outer main zone dilution air holes in line with the carburetor tubes was eliminated. These changes were directed at reducing carburetor tube jet penetration, the apparent cause of the hot streaks. In addition, the feather seals were modified at two inner liner locations and one outer liner location to enhance cooling effectiveness. The leading edge was cut back 0.635 cm (0.250 in) and a slot was installed, as shown in Figure 5.3.2-5, to provide the supplementary leakage flow for cooling the selected seals.

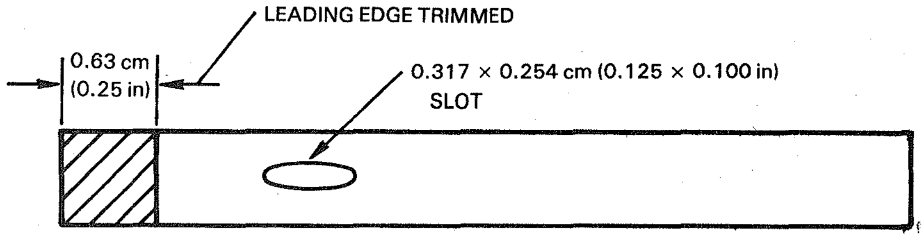
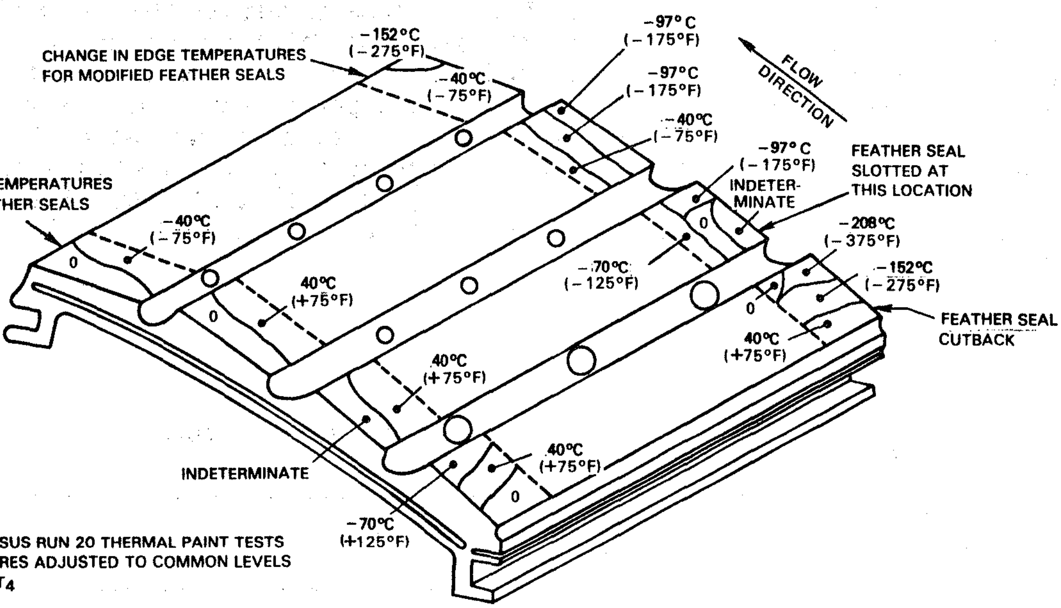


Figure 5.3.2-5 Feather Seal Modifications

A post-test thermal paint analysis indicated only a minor overall change in streak temperatures on the inner segment. The only exception was an estimated reduction of up to 148°C (300°F) at the modified feather seal locations, as shown in Figure 5.3.2-6. Evidently, the carburetor tube modifications were insufficient to reduce jet penetration, while the improved cooling through the feather seals proved a viable approach in reducing temperatures along the panel edges.

The analysis of thermal paint on the outer liner rear panels indicated an essentially streak-free condition and temperatures at or below the predicted nonstreak level. The elimination of the outer main zone dilution holes is believed to have contributed to this improvement. The post-test condition of the inner and outer liners are shown in Figures 5.3.2-7 and -8.

Tests with broad specification fuel (run 21) included additional testing with Jet A fuel to provide information relative to the hot streak condition along the inner wall. Before the initiation of testing, the center three pilot fuel injectors upstream of the inner liner streaks were radially relocated in order to ascertain if possible nonuniform thermal growth of the sector rig liner assembly contributed to the hot streaks. The nozzles were moved 0.474 cm (0.187 in) radially outboard. Except for this modification, the configurations used in runs 20 and 21 were identical. Parametric evaluations were also conducted to investigate the effects of pilot to main zone fuel split and pressure level. Thermal paint was not used in run 21 so results are based on liner thermocouple readings, which showed good correlation with thermal paint measurements from previous tests.



NOTES: (1) RUN 19 VERSUS RUN 20 THERMAL PAINT TESTS TEMPERATURES ADJUSTED TO COMMON LEVELS OF T_3 AND T_4

(2) REGIONS LABELED "INDETERMINATE" WHEN READINGS ARE OUTSIDE PAINT TEMPERATURE RANGE

Figure 5.3.2-6 Effect of Feather Seal Cooling Slots on Segment Edge Temperature Levels

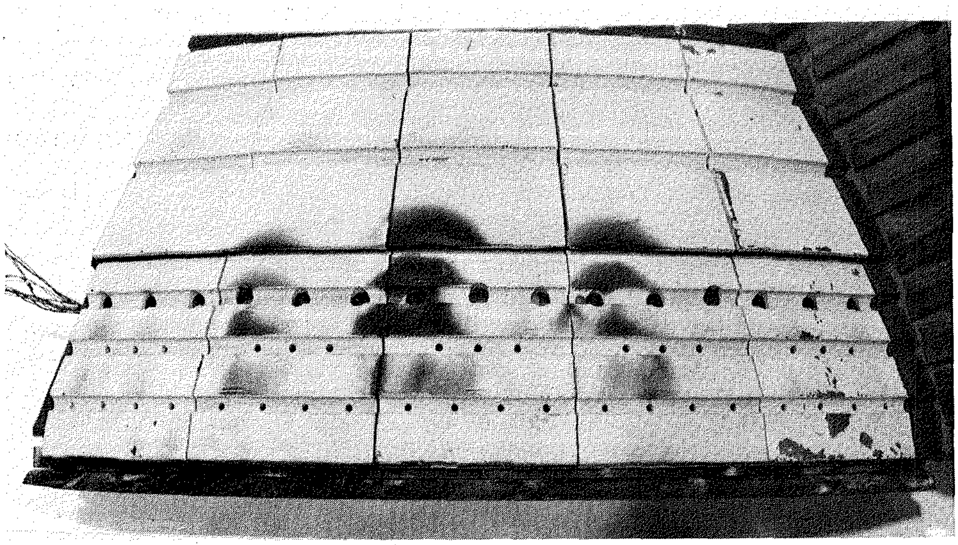


Figure 5.3.2-7 Post-Test Condition of Inner Liner Assembly (Run 20 Conditions: TT3 = 526°C (980°F), TT4 = 1304°C (2380°F), after approximately 20 minutes)

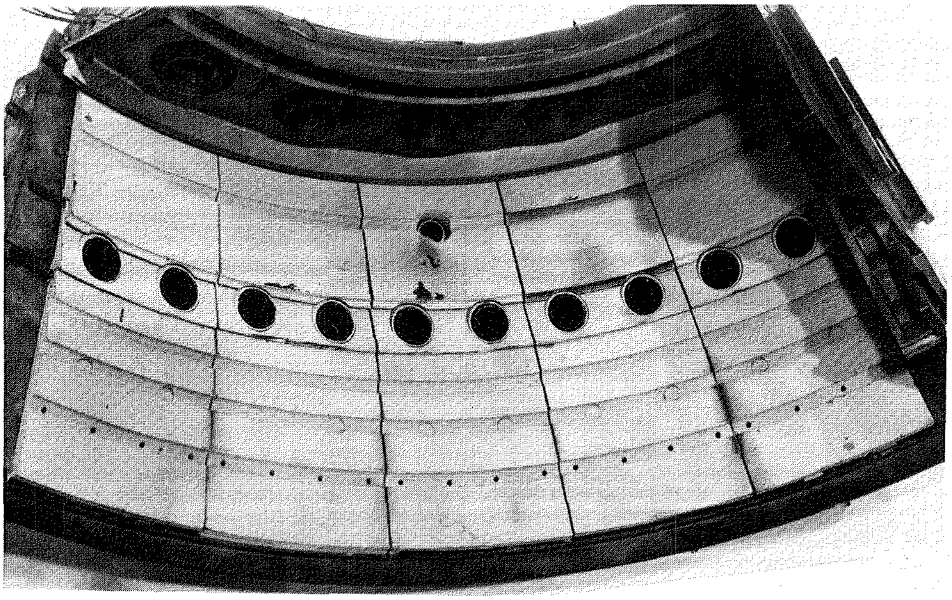


Figure 5.3.2-8 Post-Test Condition of Outer Liner Assembly (Run 20 Conditions: TT3 = 526°C (980°F), TT4 = 1 304°C (2380°F), after approximately 20 minutes)

Relocating the center three pilot fuel injectors reduced the highest (center) streak temperature approximately 65°C (150°F). The other instrumented streak increased approximately 54°C (130°F), which resulted in a near equalization of streak temperatures. The potential geometry impact on streaking will be resolved during the combustor component test.

Inner liner temperatures were affected by pressure level as well as fuel/air ratio. As shown in Figure 5.3.2-9 measured streak temperatures at 2,757,920 Pa (400 psia) were about -3 to 65°C (25 to 150°F) higher than at 2,068,440 Pa (300 psia) with the increase proportional to increasing fuel/air ratio. Inner liner streak temperature were not significantly affected by pilot to main zone fuel splits, as shown in Figure 5.3.2-10.

5.3.3 Advanced Liner Test Summary

These series of tests demonstrated the structural integrity of the segmented liner configuration as well as the capability to meet or exceed performance and emissions levels achieved with the best louvered liner configuration. Although modifications to eliminate hot streaks along the rear inner panels were not entirely successful, results indicated the potential for eliminating the streaks without tailoring cooling flows. For example, the fact that streak temperatures responded to increasing combustor fuel/air ratio indicates that local dilution may be effective in reducing temperatures. Dilution air management will be evaluated along with other techniques during subsequent combustor component testing.

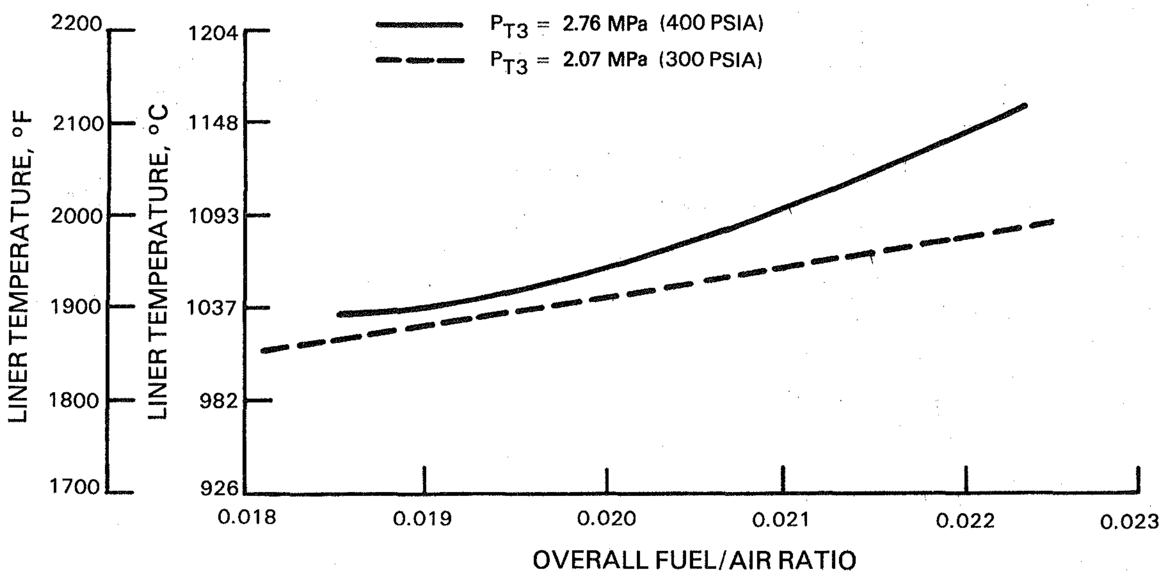


Figure 5.3.2-9 Comparison of Maximum Inner Liner Segment Temperatures at Two Pressure Levels

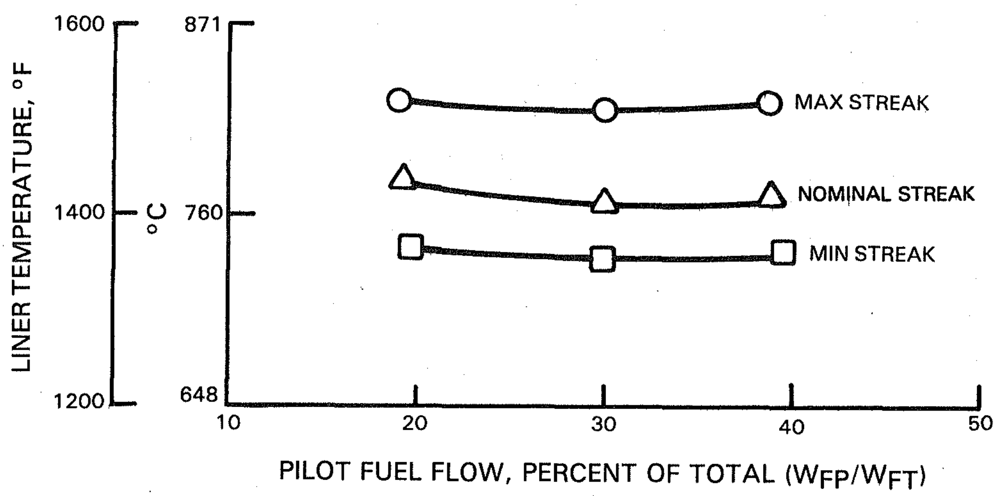


Figure 5.3.2-10 Comparison of Inner Liner Segment Temperature for Varying Pilot to Main Zone Fuel Splits

SECTION 6.0
CONCLUDING REMARKS

This program has experimentally verified the technology advances used in the Energy Efficient Engine combustor component which contribute to improved aerothermal, environmental and mechanical performance. Testing has verified the improved effectiveness of a two-stage combustion system in reducing emissions, while achieving all design performance goals. Goals for carbon monoxide and unburned hydrocarbons have been surpassed, while the goal for oxides of nitrogen was approached closely. Relative to current combustors, the low oxides of nitrogen level is considered an accomplishment, since the Energy Efficient Engine combustor operates at high pressures for better fuel economy, which in turn is inherently counterproductive to a reduction in oxides of nitrogen.

Verification of the segmented liner concept is a prerequisite for developing a liner system that can sustain the high pressure and temperature conditions predicted for future fuel efficient engines. The use of a counter-parallel FINWALL® cooling technique enhances cooling effectiveness, and ultimately the aerothermal performance of the system. The segmented approach offers several avenues in which additional gains can be obtained. At present, structural integrity has been demonstrated and durability predictions exceed the established goals. The future introduction of advanced materials and construction simplicity offer the potential to extend liner life as well as lower liner weight.

Overall, the Sector Combustor Rig Test Program has provided a firm basis and high level of confidence to proceed with the Combustor Component Rig Test Program. The technology evolved through these efforts is applicable to the next generation of gas-turbine engines. Furthermore, it has provided a significant step towards the design of a simplified, compact combustor that meets the operating demands for commercial aircraft operating in the early to mid 1990 time period.

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APPENDIXES

APPENDIX A
DATA ANALYSIS PROCEDURES

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APPENDIX A

DATA ANALYSIS PROCEDURES

PERFORMANCE DATA

Measured and calculated combustor performance parameters are listed in Table A-I and defined below.

TABLE A-I

SUMMARY OF REPORTED COMBUSTOR PERFORMANCE PARAMETERS

Parameter	Symbol	Units	Measured	Calculated
Total Airflow	W_{a3}	kg/s	X	
Total Combustor Airflow	W_{ab}	kg/s		X
Pilot Fuel Flow	$W_{f\ pri}$	kg/s	X	
Main Fuel Flow	$W_{f\ sec}$	kg/s	X	
Total Fuel Flow	$W_{f\ tot}$	kg/s	X	
Inlet Total Temperature	T_{t3}	K	X	
Inlet Total Pressure	P_{t3}	Pa	X	
Pattern Factor	PF	--		X
Inlet Air Humidity	H	gH_2O/kg air	X	
Fuel-Air Ratio	f/a	--		X

Total Combustor Airflow

The total combustor airflow is calculated by subtracting the measured inner and outer turbine cooling air bleed flows and the estimated combustor liner sidewall cooling airflow from the total airflow.

Pattern Factor

The pattern factor at the combustor exit is defined by the expression:

$$\text{Pattern Factor} = \frac{T_{t4\ max} - T_{t4\ avg.}}{T_{t4\ avg.} - T_{t3}}$$

there: $T_{t4\ max}$ = Highest local temperature observed at the combustor exit plane

$T_{t4\ avg}$ = Average combustor exit temperature

T_{t3} = Combustor inlet temperature

Fuel/Air Ratio

The fuel/air ratio is the ratio of fuel flow to total combustor airflow. Fuel/air ratio is calculated from measured values of total fuel flow and airflow. The independent fuel/air ratios for the pilot and main zones are determined by dividing the total fuel/air ratio in proportion to the measured fuel flow rates of each combustion zone. Hence, the sum of the pilot and main zone fuel/air ratios equals the total fuel/air ratio.

EMISSION DATA

Fuel/Air Ratio Calculations

Fuel/air ratios are reported on the basis of measured fuel and airflows (performance basis). In analyzing the data, emission indices are calculated using the local carbon-balance fuel/air ratios, and correlations are then made using overall average fuel/air ratios calculated on the performance basis.

Combustion Efficiency

Combustion efficiency is calculated on a deficit basis using the measured concentrations of carbon monoxide and total unburned hydrocarbons from the gas sample data. The calculation is based on the assumption that the total concentration of unburned hydrocarbons could be assigned the heating value of methane (CH_4). The equation is:

$$\eta_c = 100 - 100 \left(\frac{4343x + 21500y}{18.4\ (10)^6} \right)$$

where: x = Measured carbon monoxide concentration in g/kg fuel

y = Measured total unburned hydrocarbon concentration in g/kg fuel

Extrapolation of Rig Data to Engine Conditions

Since the sector combustor rig is unable to simulate the combustor inlet pressure at conditions above approach, the emissions data for oxides of nitrogen, carbon monoxide, and total unburned hydrocarbons obtained at the rig test conditions required correction to the engine conditions. The correlations used are described in the following paragraphs.

Correlation for Oxides of Nitrogen

Oxides of nitrogen are reported as equivalent NO_2.

The correlation used to scale oxides of nitrogen values to engine pressure levels and to correct the values for small differences between the actual rig conditions and the desired engine conditions is as follows:

$$NO_x\ \text{corr.} = NO_x\ \text{meas.} \left[\left(\frac{P_{t3\ \text{corr.}}}{P_{t3\ \text{meas.}}} \right)^{0.5} \left(\frac{V_{\text{ref. meas.}}}{V_{\text{ref. corr.}}} \right) T_{t4\ \text{meas.}} \right.$$

$$\left. e^{18.8\ (H_{\text{meas.}} - H_{\text{corr.}})} \quad e^{\left(\frac{T_{t3\ \text{corr.}} - T_{t3\ \text{meas.}}}{288} \right)} \right]$$

where NO_x = Emission index of oxides of nitrogen

P_{t3} = Inlet total pressure (atm)

T_{t3} = Inlet total temperature (K)

V_{ref} = Reference velocity (m/s)

H = Inlet specific humidity (gH_2O/kg air)

and subscripts:

corr. = Relates to value at corrected condition

meas. = Relates to value at measured condition

Correlations for Carbon Monoxide and Total Unburned Hydrocarbons

Total unburned hydrocarbons are reported as equivalent CH_4.

Emission indices for carbon monoxide and total unburned hydrocarbons are scaled to engine pressure levels by scaling inversely to inlet pressure.

Calculation of EPAP Values

Values for the Environmental Protection Agency Parameter (EPAP) are calculated on the basis of the emission indices extrapolated to engine conditions. The parameter is defined as follows:

$$EPAP = \frac{\sum_{i=1}^{4} EI_i \; W_{fi} \; TIM_i}{\sum_{i=1}^{4} F_{N_i} \; TIM_i}$$

where: EI = Emissions index

W_f = Fuel flow rate

TIM = Time in mode

i = Mode index (idle, approach, climb, takeoff)

F_N = Net thrust

The mode indices and times in each mode are defined in Table A-II.

Since the fuel flow, time in mode, and net thrust for the Energy Efficient Engine are all known for each operating condition, the calculations for this program are simplified by defining coefficients combining these terms for each operating condition. These coefficients are defined as:

$$\text{EPAP Coefficient}_c = \frac{W_{fc} \; TIM_c}{\sum_{i=1}^{4} F_{N_i} \; TIM_i}$$

where c denotes the operating condition for the particular coefficient. The resulting values for the coefficients are presented in Table A-II. With these coefficients, EPAP values could be calculated by multiplying the emission indices for each operating condition by the appropriate coefficient and summing.

TABLE A-II

DEFINITION OF EPAP CONDITIONS
AND EPAP COEFFICIENTS FOR ENERGY EFFICIENT ENGINE

Index Number	Operating Condition	Time in Mode (Minutes)	EPAP Coefficient (lb/hr/lb)
1	Idle	26.0	0.1156 (Unbled)
2	Approach	4.0	0.060
3	Climb	2.2	0.1025
4	Take-Off	0.7	0.0397

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APPENDIX B

SECTOR COMBUSTOR RIG

Louver Liner Configuration
Details of Cooling/Dilution Holes

The requirements of NASA Policy Directive NPD 2220.4 (September 14, 1970) regarding the use of SI Units for Appendix B have been waived in accordance with the provisions of paragraph 5d of that Directive by the Director of Lewis Research Center.

Conversions to obtain SI Units for the data presented in these appendixes are listed below.

°C = 5/9 (°F + 40) = 40
for interpolation 1°C = 1.8 °F

lb x 0.4536 = kilogram (kg)

in x 2.54 = centimeter (cm)

lb/in^2 (psia) x 6894.8 = pascals (pa)

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APPENDIX B

Run 1

INNER LINER S/N -

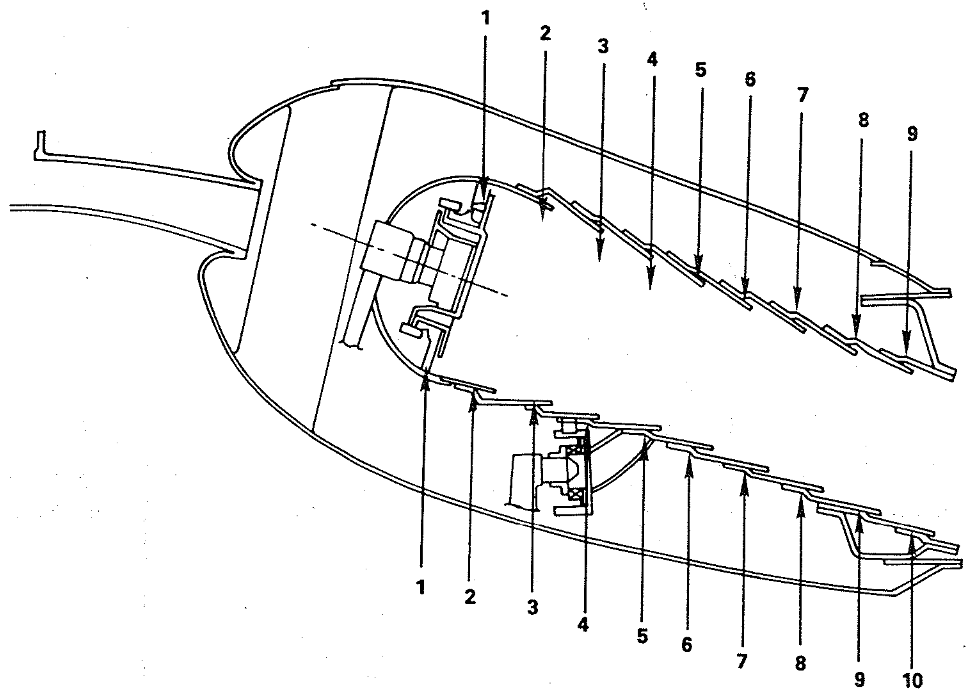
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.087	.458	.80	.366	COOL-HOOD FED
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	.102/.194	.908	.82	.745	COOL-SLOT
6	80	.098	.603	.82	.494	COOL-TOT FED
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	.500	1.379	.62	.852	ID TCA
ID LINER DILUTION(2 ROWS)***************************						
2	5	.375	.552	.60	.331	DILUTION IP
6	10	.400	1.257	.60	.754	DILUTION IM

OUTER LINER S/N-

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.088	.626	.80	.501	COOL-HOOD FED
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.046	.191	.82	.157	COOL-TOT FED
9	148	.040	.186	.82	.153	COOL-TOT FED
10	148	.040	.186	.82	.153	COOL-TOT FED
	10	****	****	***	2.400	C/T (510)
	10	****	****	***	1.700	C/T SLEEVE
	12	.421	1.670	.62	1.036	OD TCA
OD LINER DILUTION(2 ROWS)***************************						
2	4	.551	.954	.60	.572	DILUTION IP
7	10	.500	1.963	.60	1.178	DILUTION IM

TOTAL NOZZLE CENTER ACD =	0.400
TOTAL NOZZLE SWIRLER ACD =	1.050
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.481
TOTAL SIDE WALL ACD =	0.835
TOTAL ID LINER ACD =	4.383
TOTAL OD LINER ACD =	9.456
TOTAL SECTOR RIG ACD =	17.130

SYMBOL KEY
- IP-INLINE WITH PILOT NOZZLE
- BP-BETWEEN PILOT NOZZLES
- IM-INLINE WITH MAIN NOZZLES
- BM-BETWEEN MAIN NOZZLES
- ****-CHANGED FROM LAST RUN



APPENDIX B

Runs 2 and 3

INNER LINER S/N - 1

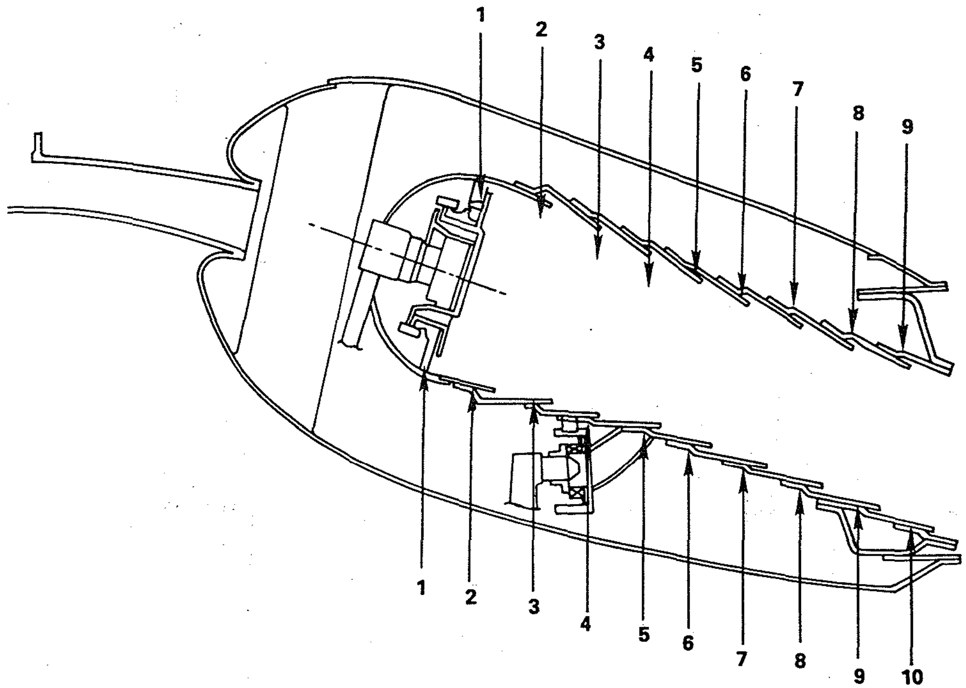
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.087	.458	.80	.366	COOL-HOOD FED
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	.102/.194	.908	.82	.745	COOL-SLOT
6	80	.098	.603	.82	.494	COOL-TOT FED
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	.500	1.379	.62	.852	ID TCA
ID LINER DILUTION(1 ROWS)*****************************						
6	11	.400	1.382	.60	.829	DILUTION BM ****

OUTER LINER S/N- 1

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.088	.626	.80	.501	COOL-HOOD FED
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.046	.191	.82	.157	COOL-TOT FED
9	148	.040	.186	.82	.153	COOL-TOT FED
10	148	.040	.186	.82	.153	COOL-TOT FED
	10	****	****	***	2.400	C/T (510)
	10	****	****	***	1.700	C/T SLEEVE
	12	.421	1.670	.62	1.036	OD TCA
OD LINER DILUTION(1 ROWS)*****************************						
7	10	.500	1.963	.60	1.178	DILUTION IM

TOTAL NOZZLE CENTER ACD =	0.150
TOTAL NOZZLE SWIRLER ACD =	1.200
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.481
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	4.127
TOTAL OD LINER ACD =	8.974
TOTAL SECTOR RIG ACD =	16.477

SYMBOL KEY
IP-INLINE WITH PILOT NOZZLE
BP-BETWEEN PILOT NOZZLES
IM-INLINE WITH MAIN NOZZLES
BM-BETWEEN MAIN NOZZLES
****-CHANGED FROM LAST RUN



APPENDIX B

Run 4

INNER LINER S/N - 1

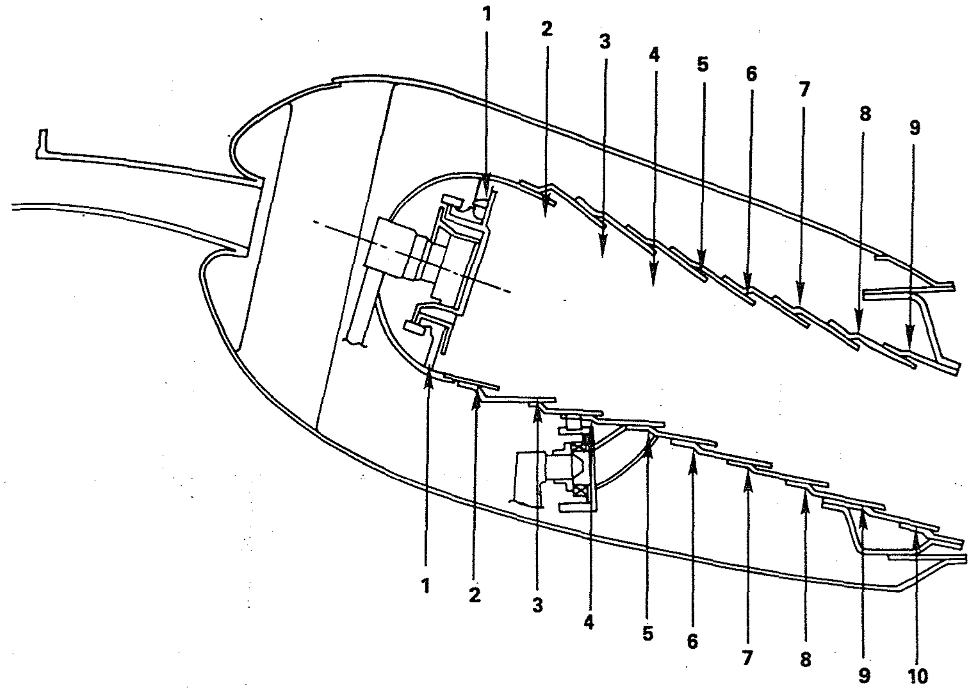
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.062	.232	.80	.186	COOL-HOOD FED ****
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	.102/.194	.908	.82	.745	COOL-SLOT
6	80	.098	.603	.82	.494	COOL-TOT FED
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	****	1.128	.62	.699	ID TCA ****
ID LINER DILUTION(1 ROWS)****************************						
6	11	.250	.540	.60	.324	DILUTION BM ****

OUTER LINER S/N- 1

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.062	.311	.80	.249	COOL-HOOD FED ****
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.062	.347	.82	.285	COOL-TOT FED ****
9	148	.052	.314	.82	.258	COOL-TOT FED ****
10	148	.052	.314	.82	.258	COOL-TOT FED ****
	10	****	****	***	2.400	C/T (510)
	10	****	****	***	1.700	C/T SLEEVE
	12	.***	1.434	.62	0.889	OD TCA ****
OD LINER DILUTION(1 ROWS)****************************						
7	10	.420	1.385	.60	.831	DILUTION IM ****

TOTAL NOZZLE CENTER ACD = 0.400
TOTAL NOZZLE SWIRLER ACD = 1.050
TOTAL BULKHEAD COOLING ACD = 0.441
TOTAL GUIDE PURGE ACD = 0.121
TOTAL SIDE WALL ACD = 1.104
TOTAL ID LINER ACD = 3.289
TOTAL OD LINER ACD = 8.566
TOTAL SECTOR RIG ACD = 14.741

SYMBOL KEY
IP-INLINE WITH PILOT NOZZLE
BP-BETWEEN PILOT NOZZLES
IM-INLINE WITH MAIN NOZZLES
BM-BETWEEN MAIN NOZZLES
****-CHANGED FROM LAST RUN



APPENDIX B

Run 5

INNER LINER S/N - 1

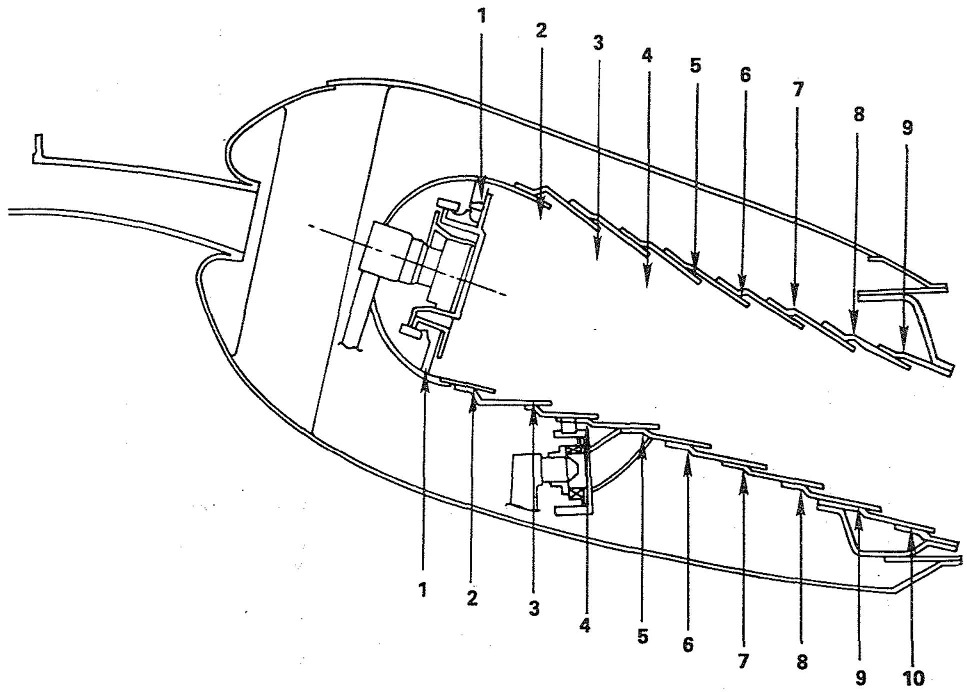
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.062	.232	.80	.186	COOL-HOOD FED ****
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	.102/.194	.908	.82	.745	COOL-SLOT
6	80	.098	.603	.82	.494	COOL-TOT FED
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	****	1.128	.62	.699	ID TCA ****
ID LINER DILUTION(1 ROWS)******************************						
6	11	.250	.540	.60	.324	DILUTION BM ****

OUTER LINER S/N- 1

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.062	.311	.80	.249	COOL-HOOD FED ****
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.062	.347	.82	.285	COOL-TOT FED ****
9	148	.052	.314	.82	.258	COOL-TOT FED ****
10	148	.052	.314	.82	.258	COOL-TOT FED ****
	10	****	****	***	2.400	C/T (510)
	10	****	****	***	1.700	C/T SLEEVE
	12	.***	1.434	.62	0.889	OD TCA ****
OD LINER DILUTION(1 ROWS)******************************						
7	10	.420	1.385	.60	.831	DILUTION IM ****

TOTAL NOZZLE CENTER ACD =	0.350
TOTAL NOZZLE SWIRLER ACD =	0.750
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.121
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	3.289
TOTAL OD LINER ACD =	8.566
TOTAL SECTOR RIG ACD =	14.691

SYMBOL KEY
- IP-INLINE WITH PILOT NOZZLE
- BP-BETWEEN PILOT NOZZLES
- IM-INLINE WITH MAIN NOZZLES
- BM-BETWEEN MAIN NOZZLES
- ****-CHANGED FROM LAST RUN



APPENDIX B

Run 6

INNER LINER S/N - 1

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.062	.232	.80	.186	COOL-HOOD FED
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	.102/.194	.908	.82	.745	COOL-SLOT
6	80	.098	.603	.82	.494	COOL-TOT FED
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	****	1.890	.62	1.172	ID TCA ****

ID LINER DILUTION(0 ROWS)****************************

OUTER LINER S/N- 1

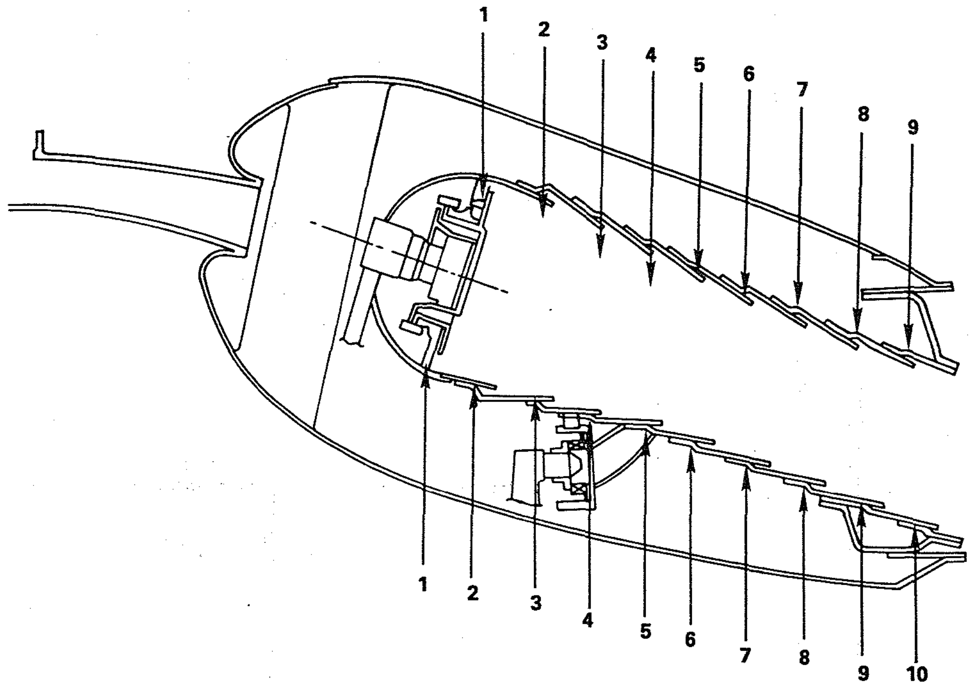
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.062	.311	.80	.249	COOL-HOOD FED
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.062	.347	.82	.285	COOL-TOT FED
9	148	.052	.314	.82	.258	COOL-TOT FED
10	148	.052	.314	.82	.258	COOL-TOT FED
	10	****	****	***	2.400	C/T (510)
	10	****	****	***	1.700	C/T SLEEVE
	12	.***	2.110	.62	1.308	OD TCA ****

OD LINER DILUTION(1 ROWS)****************************

7	10	.344	0.929	.60	.558	DILUTION IM ****

TOTAL NOZZLE CENTER ACD =	0.350
TOTAL NOZZLE SWIRLER ACD =	0.750
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.121
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	3.438
TOTAL OD LINER ACD =	8.712
TOTAL SECTOR RIG ACD =	14.916

SYMBOL KEY
IP-INLINE WITH PILOT NOZZLE
BP-BETWEEN PILOT NOZZLES
IM-INLINE WITH MAIN NOZZLES
BM-BETWEEN MAIN NOZZLES
****-CHANGED FROM LAST RUN



APPENDIX B

Run 7

INNER LINER S/N - 1

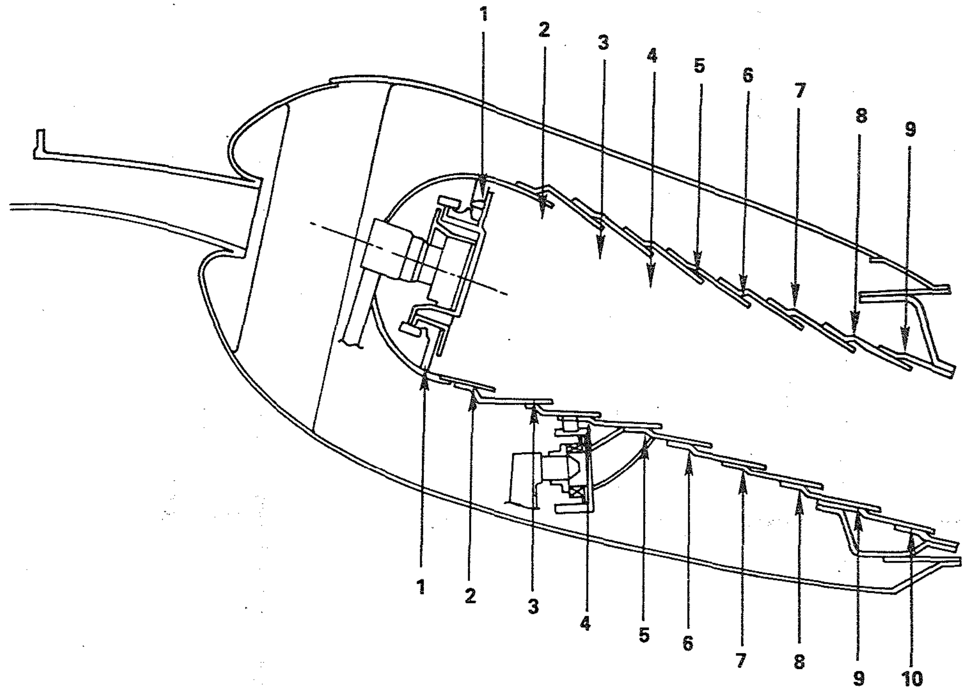
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE	
1	77	.062	.232	.80	.186	COOL-HOOD FED	
2	78	.055	.185	.82	.152	COOL-TOT FED	
3	104	.040	.131	.82	.107	COOL-TOT FED	
4	105	.040	.132	.82	.108	COOL-TOT FED	
5	52	****	****	.82	.470	COOL-SLOT	****
6	80	.098	.603	.82	.494	COOL-TOT FED	
7	85	.063	.265	.82	.217	COOL-TOT FED	
8	112	.040	.141	.82	.116	COOL-TOT FED	
9	91	.049	.172	.82	.141	COOL-TOT FED	
	7	****	1.890	.62	1.172	ID TCA	
ID LINER DILUTION(1 ROWS)****************************							
8	11	.232	.465	.60	.279	DILUTION BM ****	

OUTER LINER S/N- 1

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE	
1	103	.062	.311	.80	.249	COOL-HOOD FED	
2	108	.046	.179	.82	.147	COOL-TOT FED	
3	100	.046	.166	.82	.136	COOL-TOT FED	
4	108	.041	.143	.82	.117	COOL-TOT FED	
5	24	.102/.194	.492	.82	.403	COOL SLOT	
6	108	.094	.749	.82	.614	COOL-TOT FED	
7	109	.063	.340	.82	.279	COOL-TOT FED	
8	115	.062	.347	.82	.285	COOL-TOT FED	
9	148	.052	.314	.82	.258	COOL-TOT FED	
10	148	.052	.314	.82	.258	COOL-TOT FED	
	10	****	****	***	2.700	C/T (700)	****
	10	****	****	***	1.700	C/T SLEEVE	
	12	.***	1.434	.62	0.889	OD TCA	****
OD LINER DILUTION(1 ROWS)****************************							
7	10	.344	0.929	.60	.558	DILUTION IM	

TOTAL NOZZLE CENTER ACD =	0.225
TOTAL NOZZLE SWIRLER ACD =	0.750
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.121
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	3.442
TOTAL OD LINER ACD =	8.593
TOTAL SECTOR RIG ACD =	14.801

SYMBOL KEY
IP-INLINE WITH PILOT NOZZLE
BP-BETWEEN PILOT NOZZLES
IM-INLINE WITH MAIN NOZZLES
BM-BETWEEN MAIN NOZZLES
****-CHANGED FROM LAST RUN



APPENDIX B

Run 8

INNER LINER S/N - 2

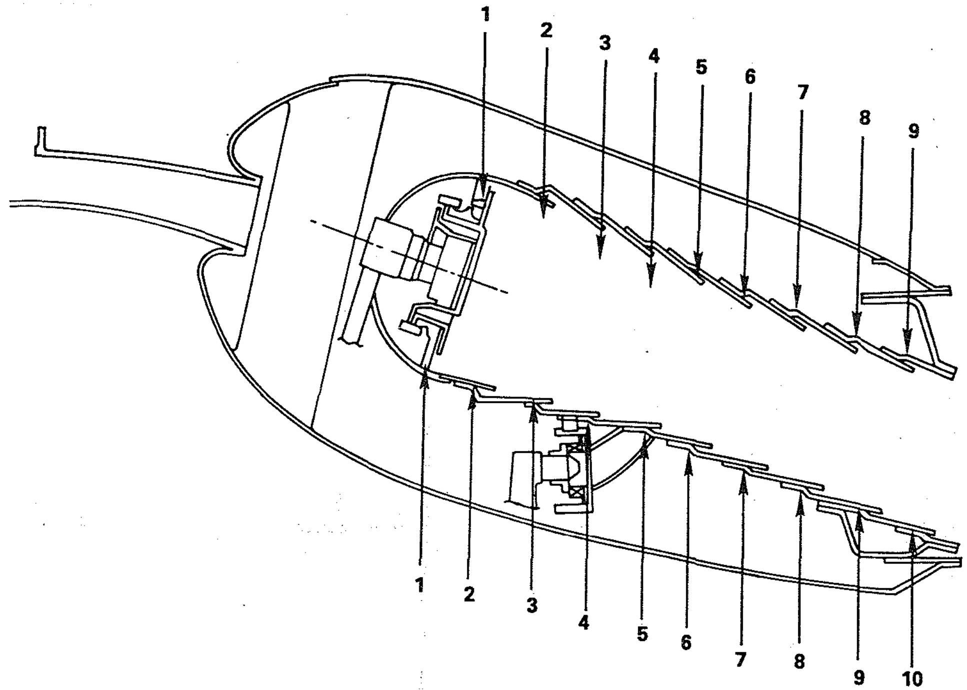
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.062	.232	.80	.186	COOL-HOOD FED
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	.102/.194	.908	.82	.745	COOL-SLOT
6	80	.098	.603	.82	.494	COOL-TOT FED
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	****	1.128	.62	.699	ID TCA
ID LINER DILUTION(1 ROWS)***************************						
6	11	.250	.540	.60	.324	DILUTION BM ****

OUTER LINER S/N- 2

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.062	.311	.80	.249	COOL-HOOD FED
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.062	.347	.82	.285	COOL-TOT FED
9	148	.052	.314	.82	.258	COOL-TOT FED
10	148	.052	.314	.82	.258	COOL-TOT FED
	10	****	****	***	2.400	C/T (510)
	10	****	****	***	1.150	C/T SLEEVE/SWIRL
	12	.***	1.434	.62	0.889	OD TCA ****
OD LINER DILUTION(1 ROWS)***************************						
7	10	.420	1.385	.60	.831	DILUTION IM ****

TOTAL NOZZLE CENTER ACD =	0.230
TOTAL NOZZLE SWIRLER ACD =	0.930
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.121
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	3.289
TOTAL OD LINER ACD =	8.016
TOTAL SECTOR RIG ACD =	14.131

SYMBOL KEY
IP-INLINE WITH PILOT NOZZLE
BP-BETWEEN PILOT NOZZLES
IM-INLINE WITH MAIN NOZZLES
BM-BETWEEN MAIN NOZZLES
****-CHANGED FROM LAST RUN



APPENDIX B

Run 9

INNER LINER S/N - 2

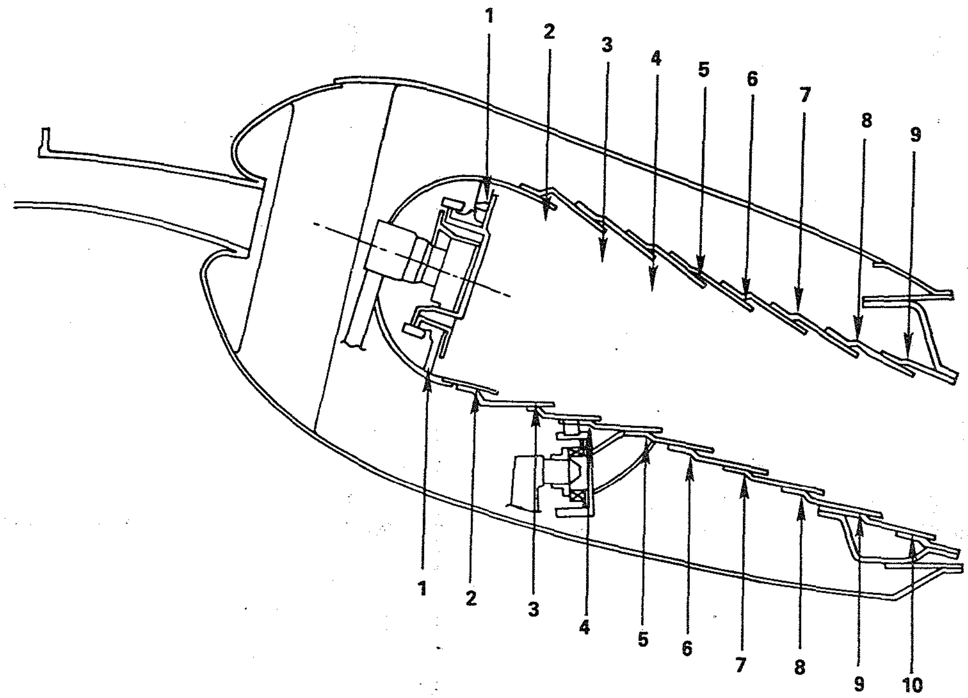
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.062	.232	.80	.186	COOL-HOOD FED
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	****	****	.82	.470	COOL-SLOT ****
6	80	.073	.335	.82	.275	COOL-TOT FED ****
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	****	1.128	.62	.699	ID TCA
ID LINER DILUTION(2 ROWS)***************************						
6	11	.250	.540	.60	.324	DILUTION BM ****
7	10	.700/.300	2.807	.60	1.684	DIL SLOTS IM ****

OUTER LINER S/N- 2

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.062	.311	.80	.249	COOL-HOOD FED
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.062	.347	.82	.285	COOL-TOT FED
9	148	.052	.314	.82	.258	COOL-TOT FED
10	148	.052	.314	.82	.258	COOL-TOT FED
	10	****	****	***	2.400	C/T (510)
	10	****	****	***	1.150	C/T SLEEVE/SWIRL
	12	.***	1.434	.62	0.889	OD TCA
OD LINER DILUTION(1 ROWS)***************************						
7	10	.420	1.385	.60	.831	DILUTION IM

TOTAL NOZZLE CENTER ACD =	0.230
TOTAL NOZZLE SWIRLER ACD =	0.930
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.121
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	4.479
TOTAL OD LINER ACD =	8.016
TOTAL SECTOR RIG ACD =	15.321

SYMBOL KEY
- IP-INLINE WITH PILOT NOZZLE
- BP-BETWEEN PILOT NOZZLES
- IM-INLINE WITH MAIN NOZZLES
- BM-BETWEEN MAIN NOZZLES
- ****-CHANGED FROM LAST RUN



APPENDIX B

Run 10

INNER LINER S/N - 2

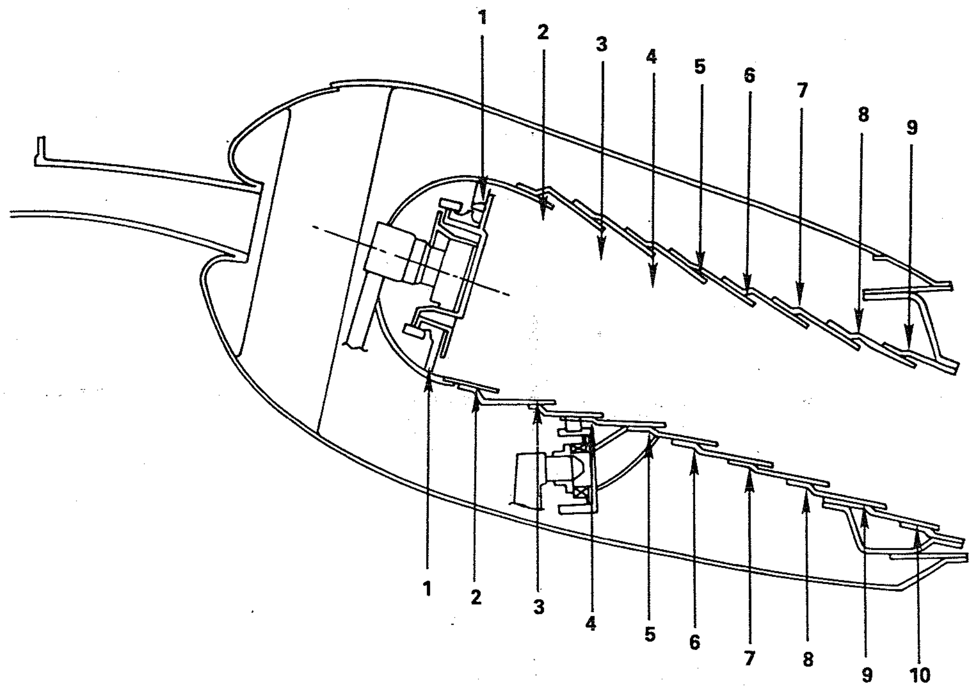
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.062	.232	.80	.186	COOL-HOOD FED
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	****	****	.82	.470	COOL-SLOT
6	80	.073	.335	.82	.275	COOL-TOT FED
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	****	1.128	.62	.699	ID TCA
ID LINER DILUTION(3 ROWS)***************************						
6	11	.453	1.773	.60	1.064	DILUTION BM ****
7	21	.125	.258	.60	.155	DILUTION IM ****
8	20	.125	.245	.60	.147	DILUTION ****

OUTER LINER S/N- 2

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.062	.311	.80	.249	COOL-HOOD FED
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.062	.347	.82	.285	COOL-TOT FED
9	148	.052	.314	.82	.258	COOL-TOT FED
10	148	.052	.314	.82	.258	COOL-TOT FED
	10	****	****	***	2.700	C/T (510) ****
	10	****	****	***	1.150	C/T SLEEVE/SWIRL
	12	.***	1.434	.62	0.889	OD TCA
OD LINER DILUTION(2 ROWS)***************************						
7	10	.420	1.385	.60	.831	DILUTION IM
9	20	.125	.245	.60	.147	DILUTION ****

TOTAL NOZZLE CENTER ACD =	0.230
TOTAL NOZZLE SWIRLER ACD =	0.930
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.121
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	3.837
TOTAL OD LINER ACD =	8.463
TOTAL SECTOR RIG ACD =	15.126

SYMBOL KEY
- IP-INLINE WITH PILOT NOZZLE
- BP-BETWEEN PILOT NOZZLES
- IM-INLINE WITH MAIN NOZZLES
- BM-BETWEEN MAIN NOZZLES
- ****-CHANGED FROM LAST RUN



APPENDIX B

Run 11

INNER LINER S/N - 1

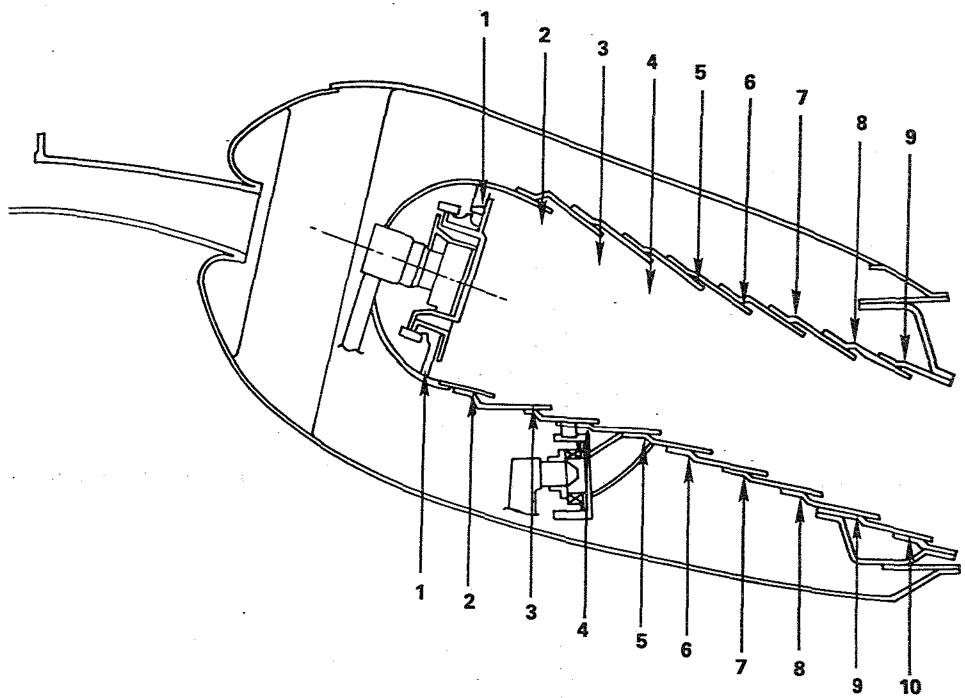
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.062	.232	.80	.186	COOL-HOOD FED
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	****	****	.82	.470	COOL-SLOT
6	80	.073	.335	.82	.275	COOL-TOT FED****
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	****	1.128	.62	0.699	ID TCA
ID LINER DILUTION(2 ROWS)***************************						
7	21	.290	1.387	.60	.832	DILUTION ****
8	11	.232	.465	.60	.279	DILUTION BM ****

OUTER LINER S/N- 1

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.062	.311	.80	.249	COOL-HOOD FED
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.062	.347	.82	.285	COOL-TOT FED
9	148	.052	.314	.82	.258	COOL-TOT FED
10	148	.052	.314	.82	.258	COOL-TOT FED
	10	****	****	***	2.400	C/T (700) ****
	10	****	****	***	1.450	C/T SLEEVE
	12	.***	1.434	.62	0.889	OD TCA
OD LINER DILUTION(2 ROWS)***************************						
7	10	.344	0.929	.60	.558	DILUTION IM
9	10	.250	.491	.60	.295	DILUTION ****

TOTAL NOZZLE CENTER ACD = 0.150
TOTAL NOZZLE SWIRLER ACD = 0.835
TOTAL BULKHEAD COOLING ACD = 0.441
TOTAL GUIDE PURGE ACD = 0.121
TOTAL SIDE WALL ACD = 1.104
TOTAL ID LINER ACD = 3.582
TOTAL OD LINER ACD = 8.338
TOTAL SECTOR RIG ACD = ******

SYMBOL KEY
IP-INLINE WITH PILOT NOZZLE
BP-BETWEEN PILOT NOZZLES
IM-INLINE WITH MAIN NOZZLES
BM-BETWEEN MAIN NOZZLES
****-CHANGED FROM LAST RUN



APPENDIX B

Run 15

INNER LINER S/N - 2

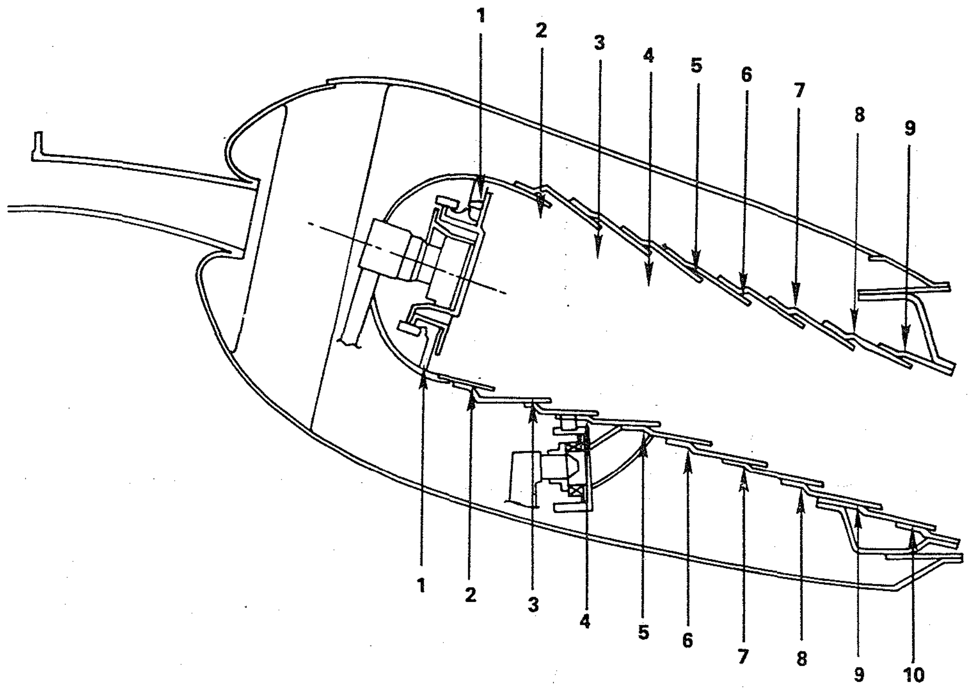
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.062	.232	.80	.186	COOL-HOOD FED
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	****	****	.82	.470	COOL-SLOT
6	80	.073	.335	.82	.275	COOL-TOT FED
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	****	1.128	.62	.699	ID TCA
ID LINER DILUTION(4 ROWS)****************************						
4	11	.360	1.119	.60	0.672	DILUTION ****
6	11	.275	0.653	.60	0.392	DILUTION ***
7	21	.125	.258	.60	.155	DILUTION IM
8	20	.125	.245	.60	.147	DILUTION

OUTER LINER S/N- 2

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.062	.311	.80	.249	COOL-HOOD FED
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.062	.347	.82	.285	COOL-TOT FED
9	148	.052	.314	.82	.258	COOL-TOT FED
10	148	.052	.314	.82	.258	COOL-TOT FED
	10	****	****	***	2.700	C/T (510) ****
	10	****	****	***	1.150	C/T SLEEVE/SWIRL
	12	.***	1.434	.62	0.889	OD TCA
OD LINER DILUTION(3 ROWS)****************************						
7	10	.380	1.134	.60	.680	DILUTION IM
8	21	.125	0.258	.60	.155	DILUTION ***
9	20	.125	.245	.60	.147	DILUTION

TOTAL NOZZLE CENTER ACD =	0.150
TOTAL NOZZLE SWIRLER ACD =	0.835
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.121
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	3.837
TOTAL OD LINER ACD =	8.467
TOTAL SECTOR RIG ACD =	14.955

SYMBOL KEY
- IP-INLINE WITH PILOT NOZZLE
- BP-BETWEEN PILOT NOZZLES
- IM-INLINE WITH MAIN NOZZLES
- BM-BETWEEN MAIN NOZZLES
- ****-CHANGED FROM LAST RUN



APPENDIX B

Run 16

INNER LINER S/N - 2

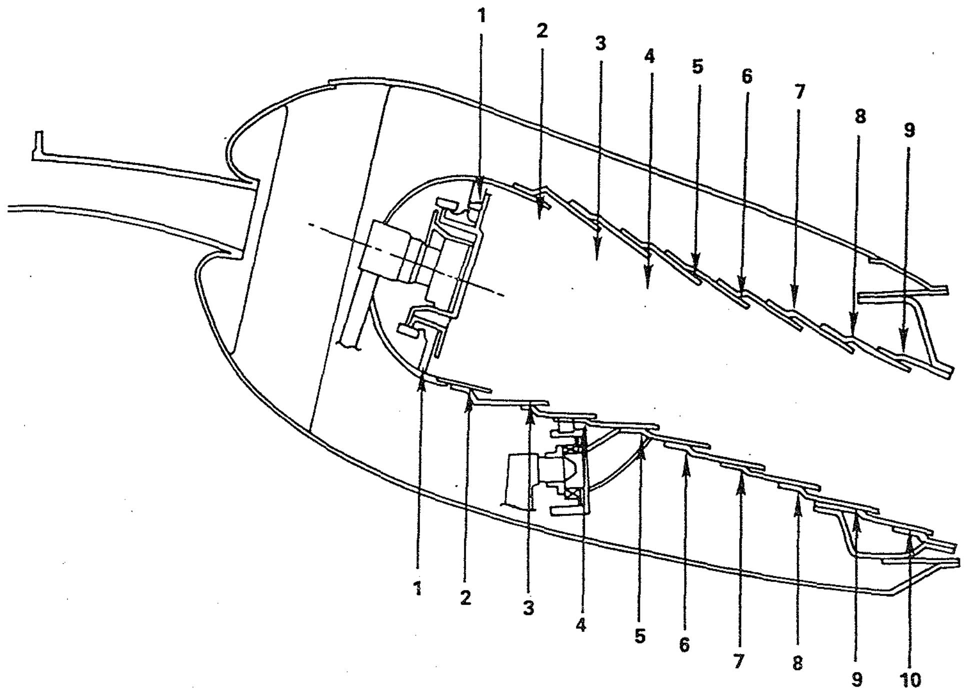
LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	77	.062	.232	.80	.186	COOL-HOOD FED
2	78	.055	.185	.82	.152	COOL-TOT FED
3	104	.040	.131	.82	.107	COOL-TOT FED
4	105	.040	.132	.82	.108	COOL-TOT FED
5	52	****	****	.82	.470	COOL-SLOT
6	80	.073	.335	.82	.275	COOL-TOT FED
7	85	.063	.265	.82	.217	COOL-TOT FED
8	112	.040	.141	.82	.116	COOL-TOT FED
9	91	.049	.172	.82	.141	COOL-TOT FED
	7	****	1.128	.62	.699	ID TCA
ID LINER DILUTION(2 ROWS)***************************						
6	11	.453	1.773	.60	1.064	DILUTION BM ****
7	21	.125	.258	.60	.155	DILUTION IM ****
8	20	.125	.245	.60	.147	DILUTION ****

OUTER LINER S/N- 2

LOUV	NUMBER	DIAMETER	AREA	CD	ACD	HOLE TYPE
1	103	.062	.311	.80	.249	COOL-HOOD FED
2	108	.046	.179	.82	.147	COOL-TOT FED
3	100	.046	.166	.82	.136	COOL-TOT FED
4	108	.041	.143	.82	.117	COOL-TOT FED
5	24	.102/.194	.492	.82	.403	COOL SLOT
6	108	.094	.749	.82	.614	COOL-TOT FED
7	109	.063	.340	.82	.279	COOL-TOT FED
8	115	.062	.347	.82	.285	COOL-TOT FED
9	148	.052	.314	.82	.258	COOL-TOT FED
10	148	.052	.314	.82	.258	COOL-TOT FED
	10	****	****	***	2.700	C/T (700:) ****
	10	****	****	***	1.150	C/T SLEEVE/SWIRL
	12	.***	1.434	.62	0.889	OD TCA
OD LINER DILUTION(1 ROWS)***************************						
7	10	.420	1.385	.60	.831	DILUTION IM
9	20	.125	.245	.60	.147	DILUTION ****

TOTAL NOZZLE CENTER ACD =	0.150
TOTAL NOZZLE SWIRLER ACD =	0.835
TOTAL BULKHEAD COOLING ACD =	0.441
TOTAL GUIDE PURGE ACD =	0.121
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	3.837
TOTAL OD LINER ACD =	8.463
TOTAL SECTOR RIG ACD =	14.951

SYMBOL KEY
- IP-INLINE WITH PILOT NOZZLE
- BP-BETWEEN PILOT NOZZLES
- IM-INLINE WITH MAIN NOZZLES
- BM-BETWEEN MAIN NOZZLES
- ****-CHANGED FROM LAST RUN



APPENDIX B

Runs 18 and 19

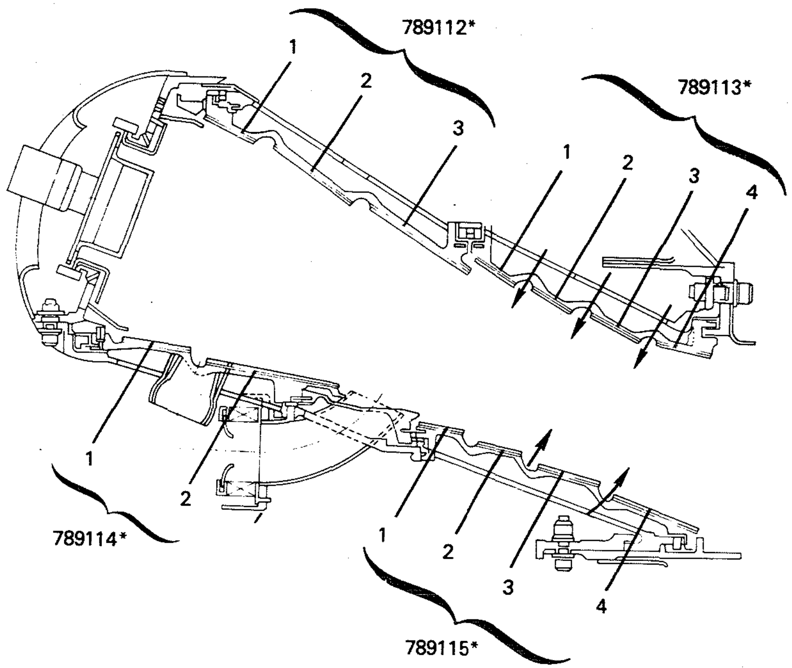
INNER LINER S/N - 3

PART	PANEL	DIAMETER	NUMBER	CD	ACDTOT	HOLE TYPE
789112	1				.228	COOLING
789112	2				.224	COOLING
789112	3				.237	COOLING
789113	1				.232	COOLING
789113	2				.315	COOLING
789113	3				.360	COOLING
789113	4				.365	COOLING
789113	1-2	.388	15	.60	1.064	DILUTION
789113	2-3	.148	15	.60	.155	DILUTION
789113	3-4	.125	20	.60	.147	DILUTION
******		.283	18	.62	.702	TCA

OUTER LINER S/N- 3

PART	PANEL	DIAMETER	NUMBER	CD	ACDTOT	HOLE TYPE
789114	1				.361	COOLING
789114	2				.379	COOLING
789115	1				.424	COOLING
789115	2				.386	COOLING
789115	3				.410	COOLING
789115	4				.433	COOLING
C/T LOUV		.072	115	.82	.384	COOLING
C/T					2.400	CORE
C/T SLEEVE					1.700	SECONDARY
789115	2-3	.420	10	.60	.831	DILUTION
789115	3-4	.125	20	.60	.147	DILUTION
******					.889	TCA

TOTAL NOZZLE CENTER ACD =	0.150
TOTAL NOZZLE SWIRLER ACD =	0.835
TOTAL BULKHEAD COOLING ACD =	0.454
TOTAL GUIDE PURGE ACD =	0.131
TOTAL SIDE WALL ACD =	1.104
TOTAL ID LINER ACD =	4.029
TOTAL OD LINER ACD =	8.744
TOTAL SECTOR RIG ACD =	15.447



* EACH SEGMENT COVERS 15° CIRCUMFERENTIAL ARC

APPENDIX B

Runs 20 and 21

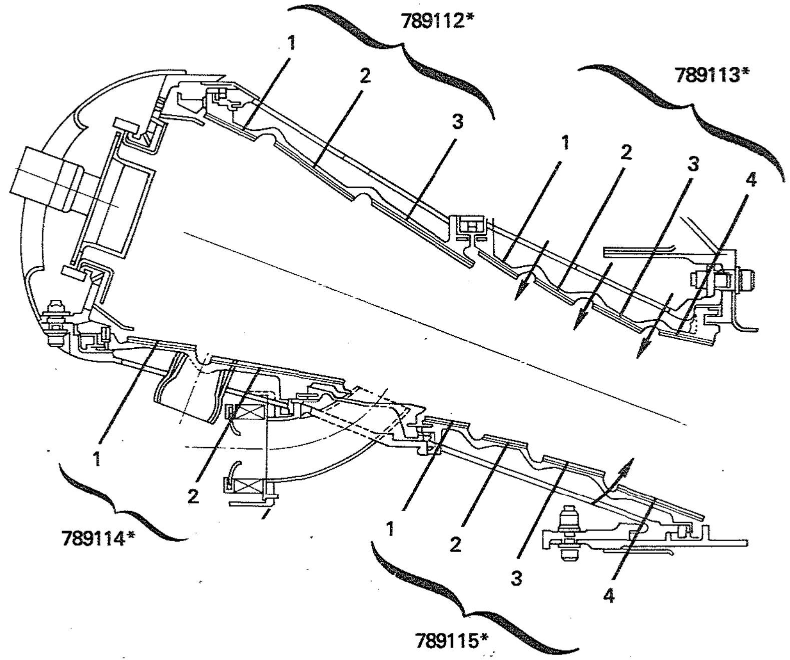
INNER LINER S/N - 3

PART	PANEL	DIAMETER	NUMBER	CD	ACDTOT	HOLE TYPE
789112	1				.228	COOLING
789112	2				.224	COOLING
789112	3				.237	COOLING
789113	1				.232	COOLING
789113	2				.315	COOLING
789113	3				.360	COOLING
789113	4				.365	COOLING
789113	1-2	.388	15	.60	1.064	DILUTION
789113	2-3	.148	15	.60	.155	DILUTION
789113	3-4	.125	20	.60	.147	DILUTION
******		.283	18	.62	.702	TCA

OUTER LINER S/N- 3

PART	PANEL	DIAMETER	NUMBER	CD	ACDTOT	HOLE TYPE
789114	1				.361	COOLING
789114	2				.379	COOLING
789115	1				.424	COOLING
789115	2				.386	COOLING
789115	3				.410	COOLING
789115	4				.433	COOLING
C/T LOUV		.072	115	.82	.384	COOLING
C/T					2.400	CORE
C/T SLEEVE					1.700	SECONDARY
789115	3-4	.125	20	.60	.147	DILUTION
******					.889	TCA

TOTAL NOZZLE CENTER ACD = 0.150
TOTAL NOZZLE SWIRLER ACD = 0.835
TOTAL BULKHEAD COOLING ACD = 0.454
TOTAL GUIDE PURGE ACD = 0.131
TOTAL SIDE WALL ACD = 1.104
TOTAL ID LINER ACD = 4.029
TOTAL OD LINER ACD = 8.744
TOTAL SECTOR RIG ACD = 15.447



* EACH SEGMENT COVERS 15° CIRCUMFERENTIAL ARC

APPENDIX C
EXPERIMENTAL TEST DATA

The requirements of NASA Policy Directive NPD 2220.4 (September 14, 1970) regarding the use of SI Units for Appendix C have been waived in accordance with the provisions of paragraph 5d of that Directive by the Director of Lewis Research Center.

Conversions to obtain SI Units for the data presented in these appendixes are listed below.

°C = 5/9 (°F + 40) = 40
for interpolation 1°C = 1.8 °F

lb x 0.4536 = kilogram (kg)

in x 2.54 = centimeter (cm)

lb/in^2 (psia) x 6894.8 = pascals (pa)

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APPENDIX C
DATA SUMMARY SHEET
(Run 1)

									Rig Reference			Engine Reference				
Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	CO EI	THC EI	NO_x EI	CO EI	THC EI	NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
1	131	16.346	13.403	623.1	193.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	14	18.340	14.901	615.0	196.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	151	21.660	17.559	618.3	173.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	15	21.372	17.614	621.8	194.65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	22	7.989	6.486	386.0	62.74	100.00	0.01147	0.01147	29.36	5.35	3.89	29.36	5.35	3.89	0.88964	98.68
1	21	7.832	6.538	386.9	61.76	100.00	0.01034	0.01034	59.16	26.34	2.29	59.16	26.34	2.31	0.83942	95.42
1	21	7.919	6.475	396.2	61.61	100.00	0.01339	0.01339	16.38	0.99	4.39	16.38	0.99	4.41	0.89385	99.49
1	24	7.167	5.849	396.4	60.93	100.00	0.01596	0.01596	13.57	0.53	4.84	13.57	0.53	4.90	0.87522	99.61
1	40	15.461	12.384	671.6	162.84	100.00	0.01692	0.01692	1.36	0.02	13.58	1.37	0.02	13.70	0.88953	99.96
1	40	15.440	12.100	666.9	160.74	80.92	0.01708	0.01382	2.89	48.38	9.97	2.89	48.47	10.13	0.85240	94.08
1	40	15.758	12.685	668.4	164.33	53.50	0.01546	0.00827	0.0	115.05	4.07	0.0	115.25	4.12	0.89400	86.23
1	40	15.657	14.311	671.2	168.15	49.01	0.01664	0.00816	44.50	8.45	5.76	44.58	8.47	5.70	0.99406	98.00
1	10	4.903	3.945	306.6	49.54	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	11	5.475	3.634	312.6	49.84	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	12	6.425	5.286	313.5	48.10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	20	7.089	5.803	401.2	59.91	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	46	15.370	12.780	668.5	162.35	47.55	0.01705	0.00811	42.19	7.72	5.40	42.26	7.73	5.49	0.92229	98.04
1	47	15.093	12.634	663.5	169.14	43.69	0.01745	0.00762	30.87	5.32	5.49	30.93	5.33	5.50	0.90982	98.64
1	48	15.560	12.126	664.4	166.75	38.92	0.01758	0.00684	22.48	3.09	5.63	22.52	3.09	5.65	0.94573	99.10
1	48	15.374	12.187	666.9	169.20	41.79	0.01762	0.00736	22.91	3.91	5.19	22.95	3.92	5.20	0.93808	98.99
1	48	15.374	12.187	666.9	169.20	41.79	0.01762	0.00736	22.91	3.91	5.19	22.95	3.92	5.20	0.93808	98.99
1	44	15.064	12.226	666.5	168.62	38.15	0.01857	0.00708	13.00	1.68	5.56	13.02	1.68	5.54	0.98404	99.50
1	43	15.064	11.939	667.4	161.25	44.15	0.01610	0.00711	46.29	11.99	4.21	46.38	12.01	4.28	0.96509	97.42
1	30	7.145	5.616	399.0	57.27	100.00	0.01231	0.01231	33.84	6.96	3.54	33.28	6.84	3.61	0.85751	98.36
1	31	6.683	5.055	396.3	57.97	100.00	0.01470	0.01470	21.32	2.37	4.24	20.97	2.33	4.29	0.79727	99.22
1	311	6.997	5.533	395.8	58.94	100.00	0.01395	0.01395	22.20	2.97	4.53	21.83	2.92	4.56	0.73186	99.13
1	312	6.600	5.168	410.7	57.92	100.00	0.01485	0.01485	17.51	0.88	4.56	17.22	0.86	4.60	0.78841	99.48
1	313	7.073	5.502	408.0	57.49	100.00	0.01381	0.01381	26.37	3.22	4.20	25.93	3.17	4.26	0.88497	98.99
1	314	6.939	4.475	403.7	58.95	100.00	0.01404	0.01404	27.40	3.93	4.04	26.95	3.87	4.06	0.66900	98.90
1	315	7.076	5.646	399.2	58.47	100.00	0.01380	0.01380	14.71	0.48	4.91	14.46	0.47	4.96	1.09835	99.60
1	316	7.136	5.604	399.1	58.39	100.00	0.01358	0.01358	14.09	0.95	4.11	13.86	0.93	4.15	1.05756	99.56
1	317	6.881	5.306	397.0	58.01	100.00	0.01423	0.01423	24.67	2.80	3.94	24.26	2.75	3.98	0.77149	99.09
1	318	6.838	5.529	401.1	58.38	100.00	0.01430	0.01430	20.25	1.95	4.65	19.91	1.92	4.69	0.64514	99.29
1	319	6.804	5.376	413.7	38.82	100.00	0.01435	0.01435	18.41	1.67	4.40	18.10	1.64	4.44	0.81524	99.37
1	80	7.248	5.740	400.2	60.15	100.00	0.01113	0.01113	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX C
DATA SUMMARY SHEET
(Run 2)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
2	12	19.918	15.593	398.4	173.98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	11	19.123	15.246	405.8	136.66	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	102	19.962	15.779	393.0	215.11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 -
2	10	19.983	15.779	402.0	214.31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 -
2	101	19.314	15.481	393.1	215.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 -
2	13	12.016	9.226	375.1	132.26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 -
2	22	7.009	5.318	390.6	65.44	100.00	0.01189	0.01189	9.77	1.47	6.05	9.77	1.47	5.97	1.19082	99.58
2	201	7.702	6.347	383.8	63.97	100.00	0.00991	0.00991	38.84	21.77	2.94	38.84	21.77	2.92	1.04650	96.13
2	202	7.506	5.741	393.8	65.18	100.00	0.01227	0.01227	10.15	1.24	4.76	10.15	1.24	4.70	1.03492	99.59
2	203	7.539	5.769	404.2	63.25	100.00	0.01140	0.01140	13.93	2.66	4.18	13.93	2.66	4.15	1.03821	99.30
2	205	7.565	6.162	395.1	63.68	100.00	0.01077	0.01077	19.96	6.31	3.71	19.96	6.31	3.69	1.03176	98.66
2	206	7.688	6.115	392.7	62.88	100.00	0.01025	0.01025	29.35	13.39	3.16	29.35	13.39	3.15	1.03858	97.47
2	40	16.209	13.079	671.8	167.52	100.00	0.01505	0.01505	1.69	0.04	15.23	1.69	0.04	15.22	1.04456	99.95
2	401	15.814	12.478	660.6	167.30	44.88	0.01804	0.00810	18.91	5.81	7.34	18.94	5.82	7.34	0.99619	98.84
2	402	16.062	12.758	662.2	167.13	54.44	0.01786	0.00972	19.97	5.77	9.50	20.01	5.78	9.50	1.01928	98.82
2	403	16.004	12.568	665.0	166.86	40.15	0.01812	0.00728	11.28	3.98	7.05	11.30	3.99	7.05	1.00558	99.25
2	404	15.933	12.631	664.1	166.49	35.30	0.01792	0.00633	12.32	3.79	6.31	12.34	3.79	6.32	1.01925	99.24
2	405	15.854	12.256	669.1	166.97	30.19	0.01831	0.00553	11.03	3.10	5.64	11.05	3.11	5.64	1.20639	99.37
2	22	7.195	5.746	398.1	62.64	100.00	0.01197	0.01197	14.02	2.81	4.50	14.02	2.81	4.51	0.96775	99.27
2	21	7.535	6.000	360.5	62.45	100.00	0.01025	0.01025	54.29	36.98	2.74	54.29	36.98	2.74	0.95487	93.49
2	210	7.387	5.878	373.6	58.48	100.00	0.01046	0.01046	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	210	7.504	6.164	353.9	63.21	100.00	0.01035	0.01035	45.15	34.42	2.57	45.15	34.42	2.55	0.95506	94.31
2	40	15.357	12.336	657.9	172.41	31.02	0.01795	0.00557	2.56	67.77	3.28	2.56	67.89	3.22	1.03496	92.04
2	40	15.357	12.336	657.9	172.41	31.02	0.01795	0.00557	2.56	67.77	3.28	2.56	67.89	3.22	1.03496	92.04
2	50	18.912	15.144	926.7	235.35	31.95	0.01817	0.00581	5.38	0.71	13.62	3.25	0.43	17.30	0.98447	99.79
2	511	20.128	16.074	925.6	238.40	40.29	0.01797	0.00724	1.37	0.07	12.58	0.83	0.04	15.87	0.97213	99.96
2	52	20.363	16.291	937.4	238.24	50.62	0.01762	0.00892	1.34	0.09	17.07	0.81	0.05	21.63	0.97811	99.96
2	53	19.940	15.260	936.4	240.38	60.95	0.01729	0.01054	1.78	0.07	22.27	1.08	0.04	28.02	0.94542	99.95
2	541	20.793	16.120	924.6	241.60	20.29	0.01741	0.00353	8.36	1.10	11.04	5.05	0.66	13.88	1.06041	99.68
2	55	20.455	16.698	934.0	237.33	18.10	0.01941	0.00351	9.39	0.95	12.13	5.67	0.57	15.35	1.05279	99.68
2	56	20.255	15.895	934.4	242.15	16.45	0.02138	0.00352	9.81	0.83	13.19	5.93	0.50	16.44	1.02584	99.70
2	60	19.736	15.384	996.1	241.52	17.84	0.02024	0.00361	10.18	0.85	14.33	5.41	0.45	19.48	1.02886	99.67
2	61	19.666	16.269	981.4	234.18	20.14	0.01832	0.00369	10.84	1.13	12.55	5.76	0.60	17.18	1.00211	99.60
2	62	19.195	15.296	989.7	237.77	40.38	0.01895	0.00765	1.80	0.02	15.04	0.96	0.01	20.51	0.95359	99.95
2	63	19.923	15.696	993.0	243.37	40.40	0.01970	0.00796	0.84	0.02	17.40	0.45	0.01	23.51	0.99111	99.98
2	64	20.045	15.467	987.6	245.93	37.53	0.02104	0.00790	0.56	0.02	18.70	0.30	0.01	25.07	0.99703	99.99
2	40	16.244	12.663	659.0	170.29	40.41	0.01676	0.00677	12.28	39.79	4.39	12.30	39.86	4.33	0.96964	94.93
2	42	16.299	12.782	657.5	179.60	44.86	0.01846	0.00828	8.85	18.76	6.57	8.87	18.79	6.35	1.00696	97.70

APPENDIX C
DATA SUMMARY SHEET
(Run 3)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
3	10	19.396	15.356	398.9	190.26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	101	19.618	15.431	382.1	189.38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	012	20.068	16.034	377.0	180.72	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	013	19.856	15.856	387.2	181.19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	014	19.732	15.528	393.4	191.78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	11	18.839	15.119	399.3	146.55	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	111	19.118	15.279	400.4	146.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	12	19.740	15.547	401.0	229.72	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	121	19.405	14.968	398.3	227.41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	13	8.817	6.838	344.7	103.78	100.00	0.00887	0.00887	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	131	8.785	6.847	370.9	104.24	100.00	0.00890	0.00890	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	20	7.374	5.949	400.4	62.88	100.00	0.01278	0.01278	23.38	15.99	3.90	23.38	15.99	3.89	0.84882	97.59
3	21	7.484	6.059	387.7	64.15	100.00	0.01413	0.01413	13.68	7.06	4.24	13.68	7.06	4.20	0.87737	98.87
3	22	7.768	6.047	376.5	64.23	100.00	0.01441	0.01441	11.52	4.65	4.31	11.52	4.65	4.24	0.92251	99.21
3	23	7.737	6.120	376.4	65.70	100.00	0.01505	0.01505	9.41	3.01	4.38	9.41	3.01	4.29	0.93718	99.45
3	24	7.722	6.118	372.7	61.48	100.00	0.01131	0.01131	46.51	30.56	3.84	46.51	30.56	3.88	0.89579	95.24
3	25	7.754	6.263	373.1	62.45	100.00	0.01019	0.01019	62.39	50.59	3.39	62.39	50.59	3.39	0.89302	92.59
3	40	16.075	12.709	656.3	166.58	39.90	0.01847	0.00737	18.16	22.17	3.52	18.19	22.21	3.53	0.98785	96.95
3	41	15.931	12.369	650.5	171.91	53.89	0.01967	0.01060	14.25	35.20	5.75	14.27	35.26	5.66	0.91510	95.69
3	42	15.940	12.630	651.7	173.60	47.24	0.01938	0.00915	11.29	7.35	5.74	11.31	7.37	5.65	0.95644	98.91
3	43	16.008	12.552	654.9	172.83	49.77	0.01943	0.00967	10.74	6.64	6.00	10.76	6.65	5.89	0.95564	99.01
3	44	15.854	12.791	633.7	172.76	52.51	0.01922	0.01009	11.30	7.19	6.51	11.32	7.20	6.40	0.94777	98.93
3	50	20.306	15.928	932.3	231.94	40.51	0.01856	0.00752	1.98	0.04	12.69	1.20	0.02	16.33	0.92601	99.95
3	51	20.821	16.624	934.7	231.59	30.35	0.01782	0.00541	8.93	1.32	11.21	5.39	0.80	14.42	0.96222	99.64
3	52	20.160	16.415	936.4	233.40	50.28	0.01849	0.00930	2.36	0.04	14.91	1.43	0.02	19.14	0.92266	99.94
3	53	20.337	16.164	934.7	230.75	60.39	0.01842	0.01112	3.56	0.05	18.24	2.15	0.03	23.44	0.90090	99.91
3	54	5.000	4.135	937.7	222.28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	55	20.207	16.522	939.0	234.94	30.26	0.02288	0.00692	0.73	0.02	14.33	0.44	0.01	18.29	0.99235	99.98
3	70	5.000	4.022	370.1	62.41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	71	8.028	6.837	352.1	63.70	100.00	0.01143	0.01143	48.43	37.90	3.46	48.43	37.90	3.45	0.89562	94.48

APPENDIX C
DATA SUMMARY SHEET
(Run 4)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
4	71	4.620	3.469	303.9	50.22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	10	4.650	3.770	282.4	49.67	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	10	4.175	3.493	386.5	48.37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	11	5.490	4.384	286.3	50.08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	11	5.240	4.145	322.9	48.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	11	5.350	4.268	297.4	48.84	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	12	6.300	5.264	292.3	49.46	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	12	6.130	4.921	299.1	49.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	12	6.380	5.112	295.8	49.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	20	7.416	5.993	395.6	62.68	100.00	0.01157	0.01157	5.95	0.62	3.65	5.95	0.62	3.64	1.08562	99.77
4	21	7.390	6.058	395.6	61.01	100.00	0.01039	0.01039	18.50	8.31	2.49	18.50	8.31	2.52	1.07539	98.40
4	22	7.340	5.843	389.8	61.17	100.00	0.01148	0.01148	10.34	3.09	2.97	10.34	3.09	2.98	0.99963	99.32
4	23	7.456	5.981	387.8	61.26	100.00	0.01039	0.01039	16.18	7.46	2.59	16.18	7.46	2.61	1.07048	98.58
4	24	7.380	5.990	390.1	59.82	100.00	0.00905	0.00905	75.70	10.47	1.85	75.70	10.47	1.90	0.92697	96.36
4	25	7.410	5.837	390.5	61.99	100.00	0.01245	0.01245	5.51	0.06	4.66	5.51	0.06	4.67	1.06786	99.85
4	26	7.370	5.641	390.2	62.42	100.00	0.01053	0.01053	10.74	3.97	2.80	10.74	3.97	2.80	1.06177	99.20
4	30	6.900	5.104	378.9	59.33	100.00	0.01250	0.01250	6.00	0.23	3.67	5.90	0.23	3.69	1.02783	99.82
4	301	6.790	5.061	380.0	59.09	100.00	0.01274	0.01274	5.59	0.41	3.98	5.50	0.40	3.99	1.03264	99.81
4	31	6.910	5.210	378.4	58.22	100.00	0.01126	0.01126	8.12	2.19	2.94	7.99	2.16	2.96	1.08051	99.51
4	311	6.930	5.341	374.2	58.94	100.00	0.01120	0.01120	8.31	1.86	2.99	8.17	1.83	3.02	1.08309	99.54
4	251	7.290	5.810	389.8	61.60	100.00	0.01269	0.01269	5.44	0.46	4.50	5.44	0.46	4.53	1.07700	99.80
4	241	7.239	5.811	388.2	61.12	100.00	0.01166	0.01166	5.78	0.94	3.55	5.78	0.94	3.58	1.06908	99.72
4	231	7.400	6.032	386.5	60.34	100.00	0.01021	0.01021	21.04	12.36	2.31	21.04	12.36	2.35	1.09258	97.76
4	231	7.350	5.855	393.7	59.99	100.00	0.01032	0.01032	18.40	11.15	2.32	18.40	11.15	2.36	1.08620	98.00
4	221	7.340	5.329	392.3	60.85	100.00	0.01092	0.01092	8.17	1.85	3.03	8.17	1.85	3.06	1.08701	99.54
4	211	7.300	5.849	387.9	60.97	100.00	0.01074	0.01074	11.20	4.22	2.74	11.20	4.22	2.77	1.07675	99.14
4	211	7.370	5.968	392.9	61.09	100.00	0.01066	0.01066	10.68	3.68	2.73	10.68	3.68	2.76	1.09244	99.23
4	21	7.290	6.026	390.8	59.93	100.00	0.01095	0.01095	12.58	3.09	2.83	12.58	3.09	2.90	1.07177	99.23
4	2101	7.290	5.897	387.5	59.20	100.00	0.01099	0.01099	3.81	0.61	3.07	3.81	0.61	3.14	1.17649	99.82
4	2102	7.230	5.706	390.7	59.24	100.00	0.01107	0.01107	4.97	0.70	3.20	4.97	0.70	3.28	1.27759	99.78
4	2103	7.400	5.904	390.6	59.86	100.00	0.01084	0.01084	10.68	4.16	3.37	10.68	4.16	3.44	1.18864	99.16
4	2104	7.370	5.895	389.9	60.06	100.00	0.01087	0.01087	21.34	5.94	2.79	21.34	5.94	2.85	1.03697	98.61
4	2105	7.330	5.754	390.5	60.04	100.00	0.01093	0.01093	11.98	4.35	2.48	11.98	4.35	2.53	0.93399	99.05
4	2106	7.290	5.864	391.7	59.51	100.00	0.01102	0.01102	14.65	4.44	2.47	14.65	4.44	2.52	1.05430	99.00
4	2107	7.240	5.757	389.0	59.23	100.00	0.01110	0.01110	13.85	3.23	2.58	13.85	3.23	2.64	1.06023	99.18
4	2101	7.270	5.939	393.3	60.01	100.00	0.01101	0.01101	3.62	0.75	2.97	3.62	0.75	3.03	1.17909	99.80
4	21	7.430	6.000	388.3	60.52	100.00	0.01079	0.01079	11.23	3.24	2.87	11.23	3.24	2.93	1.11596	99.26
4	40	15.990	12.647	659.0	169.90	100.00	0.01491	0.01491	1.00	0.08	17.17	1.00	0.08	17.00	1.09309	99.97
4	41	16.160	12.744	659.2	171.10	42.88	0.01784	0.00765	3.45	0.70	5.02	3.46	0.70	4.92	1.10787	99.84
4	42	16.200	12.659	660.6	175.85	47.56	0.01823	0.00867	3.97	0.60	5.85	3.97	0.60	5.73	1.08890	99.84
4	43	16.140	12.778	660.7	176.26	51.98	0.01802	0.00937	4.09	0.56	6.72	4.09	0.56	6.58	1.08930	99.84
4	44	15.970	13.015	660.6	177.14	56.06	0.01866	0.01046	3.80	0.47	8.30	3.81	0.47	8.08	1.07611	99.86
4	45	16.360	13.501	660.8	177.97	67.89	0.01785	0.01212	5.39	1.22	12.79	5.40	1.23	12.47	1.07534	99.74
4	46	16.330	12.797	660.1	175.95	100.00	0.01751	0.01751	2.98	0.47	4.96	2.98	0.47	4.82	1.09593	99.88
4	47	15.910	12.551	658.2	175.71	37.28	0.01840	0.00686	2.77	0.0	3.87	2.77	0.0	3.78	1.00784	99.94
4	48	16.440	12.969	661.2	174.19	47.11	0.01638	0.00772	5.43	2.29	3.97	5.44	2.29	3.89	1.13494	99.61
4	491	16.090	12.701	661.6	169.18	50.42	0.01560	0.00787	11.90	26.89	2.90	11.92	26.94	2.88	1.08889	96.47

APPENDIX C
DATA SUMMARY SHEET
(Run 4 Cont'd)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
4	50	20.090	15.807	922.0	229.75	39.97	0.01692	0.00677	1.98	0.01	10.26	1.20	0.01	13.09	1.11741	99.95
4	51	19.950	15.552	919.8	235.01	31.40	0.01704	0.00535	17.11	1.00	7.36	10.33	0.60	9.38	1.08673	99.48
4	52	20.220	15.952	921.9	236.08	36.03	0.01672	0.00602	2.16	0.02	10.40	1.31	0.01	13.27	1.10002	99.95
4	53	20.010	16.251	924.6	230.83	32.72	0.01832	0.00599	1.11	0.01	11.02	0.67	0.01	14.17	1.08644	99.97
4	54	20.405	15.549	924.6	235.91	30.13	0.01967	0.00593	0.59	0.01	12.28	0.36	0.01	15.64	1.11259	99.99
4	55	20.110	16.226	925.5	231.68	26.50	0.02270	0.00602	.43	0.02	13.94	0.26	0.01	17.73	1.09518	99.99
4	56	20.070	15.879	925.2	233.39	20.89	0.02018	0.00422	0.49	0.31	11.50	0.30	0.19	14.85	1.05764	99.95
4	60	19.620	15.652	985.3	237.37	24.32	0.01738	0.00423	12.60	0.50	9.95	6.70	0.27	13.57	1.08736	99.64
4	61	20.010	16.011	983.6	235.26	22.89	0.01853	0.00424	4.88	0.27	13.00	2.60	0.14	17.79	1.10602	99.85
4	62	19.837	16.575	981.7	235.16	21.06	0.02040	0.00430	3.84	0.21	14.65	2.04	0.11	20.12	1.09197	99.88
4	52	20.180	15.687	914.2	233.90	100.00	0.01582	0.01582	2.02	0.03	10.88	1.22	0.02	13.91	1.15127	99.95
4	5201	20.240	15.784	914.3	232.82	35.38	0.01669	0.00590	0.91	0.0	11.24	0.55	0.0	14.36	1.18727	99.98
4	5202	20.200	15.656	918.6	233.88	35.34	0.01668	0.00590	0.95	0.0	10.54	0.57	0.0	13.45	1.16517	99.98
4	5203	20.100	15.637	913.2	235.47	35.41	0.01681	0.00595	2.05	0.01	10.43	1.24	0.01	13.32	1.08684	99.95
4	5204	20.400	15.795	914.1	235.95	35.31	0.01650	0.00583	2.74	0.02	7.85	1.65	0.01	10.05	1.10114	99.93
4	5205	19.900	15.787	915.4	233.87	35.22	0.01683	0.00593	1.20	0.0	10.40	0.72	0.0	13.26	1.06583	99.97
4	5206	19.707	15.507	913.9	235.70	35.22	0.01712	0.00603	4.70	0.03	9.87	2.84	0.02	12.58	0.96072	99.89
4	5207	19.760	15.347	918.0	231.07	35.12	0.01707	0.00600	5.95	0.05	10.43	3.60	0.03	13.30	0.97788	99.85
4	5208	19.740	15.262	923.1	235.97	35.12	0.01707	0.00599	2.25	0.0	10.70	1.36	0.0	13.64	1.14407	99.95
4	20	7.470	5.971	391.1	60.97	100.00	0.01270	0.01270	7.06	0.26	4.46	7.06	0.26	4.51	1.09262	99.80
4	21	7.414	6.025	393.7	61.96	100.00	0.01154	0.01154	8.19	0.82	3.59	8.19	0.82	3.61	1.07643	99.71
4	22	7.490	6.013	391.5	62.95	100.00	0.00900	0.00900	10.00	2.33	2.95	10.00	2.33	2.94	1.09261	99.50
4	2201	7.430	5.961	390.4	62.83	100.00	0.01091	0.01091	9.53	2.98	2.94	9.53	2.98	2.92	0.54548	99.43
4	2202	7.480	5.841	392.8	63.49	100.00	0.01086	0.01086	10.19	2.05	2.98	10.19	2.05	2.95	1.08622	99.53
4	2203	7.430	5.909	394.8	62.25	100.00	0.01083	0.01083	12.65	2.46	2.86	12.65	2.46	2.85	1.12864	99.41
4	2204	7.390	5.895	392.1	62.52	100.00	0.01090	0.01090	10.84	1.55	3.02	10.84	1.55	3.03	1.01169	99.56
4	5201	20.350	16.131	922.9	236.69	35.66	0.01679	0.00599	6.99	0.63	11.20	4.22	0.38	14.21	1.06200	99.77
4	5202	20.433	15.958	933.5	237.55	35.54	0.01673	0.00595	10.74	0.54	10.51	6.48	0.32	13.31	1.05081	99.69
4	5203	20.420	16.081	921.9	239.80	35.36	0.01680	0.00594	3.25	0.08	10.11	1.96	0.05	12.82	1.05666	99.92
4	5204	20.155	15.603	927.8	234.39	35.29	0.01712	0.00604	5.07	0.20	9.67	3.06	0.12	12.27	1.01399	99.86

APPENDIX C
DATA SUMMARY SHEET
(Run 5)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
5	13	10.318	8.018	294.4	200.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	13	14.474	11.511	306.5	150.98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	13	14.645	11.461	305.4	150.77	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	13	14.550	11.285	305.1	151.04	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	14	16.700	13.307	305.2	151.83	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	14	16.820	13.359	302.9	151.52	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	14	16.440	12.997	303.9	152.12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	15	19.062	15.194	294.2	149.62	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	15	19.051	15.147	304.4	149.60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	15	18.724	14.915	307.6	149.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	15	19.101	15.253	306.8	149.89	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	20	7.470	5.910	393.6	63.09	100.00	0.01121	0.01121	13.79	1.18	4.56	13.79	1.18	4.53	1.07144	99.54
5	21	7.597	6.033	391.7	62.09	100.00	0.00988	0.00988	15.59	2.32	4.35	15.59	2.32	4.36	1.08657	99.36
5	22	7.581	6.038	393.3	60.82	100.00	0.00884	0.00884	17.15	3.62	4.10	17.15	3.62	4.13	1.14084	99.16
5	23	7.511	5.969	392.0	60.64	100.00	0.00867	0.00867	23.26	10.05	3.52	23.26	10.05	3.57	1.06500	98.23
5	24	7.634	6.041	394.0	64.86	100.00	0.01216	0.01216	16.20	1.06	4.80	16.20	1.06	4.76	1.09462	99.50
5	30	6.994	5.174	371.1	57.56	100.00	0.01242	0.01242	13.11	0.93	4.52	12.89	0.92	4.60	1.08038	99.57
5	31	6.817	5.117	376.9	57.99	100.00	0.01398	0.01398	11.63	0.75	4.42	11.43	0.73	4.47	1.07030	99.64
5	32	6.956	5.130	373.4	57.80	100.00	0.01305	0.01305	12.27	0.81	4.53	12.07	0.79	4.60	1.08188	99.61
5	40	15.884	12.565	647.2	168.03	100.00	0.01534	0.01534	1.58	0.05	10.77	1.58	0.05	10.69	1.04435	99.96
5	41	16.146	13.093	655.6	166.88	49.50	0.01513	0.00749	7.70	9.86	5.82	7.72	9.88	5.81	1.07518	98.67
5	42	16.134	12.902	655.1	168.33	45.63	0.01533	0.00699	6.60	6.38	5.31	6.61	6.40	5.29	1.07033	99.10
5	43	16.151	12.783	650.1	167.48	42.04	0.01525	0.00641	7.59	4.86	4.77	7.60	4.87	4.75	1.06560	99.26
5	44	16.318	13.029	654.4	166.95	50.08	0.01492	0.00747	9.41	14.35	5.77	9.43	14.38	5.76	1.09304	98.10
5	45	16.161	12.619	655.9	166.01	54.02	0.01510	0.00816	9.29	14.10	7.24	9.31	14.12	7.24	1.06495	98.13
5	46	16.079	13.197	655.6	171.71	44.54	0.01701	0.00758	4.63	1.39	7.37	4.64	1.39	7.23	1.05913	99.74
5	47	16.295	13.212	655.8	171.36	39.09	0.01675	0.00655	4.76	1.56	5.76	4.77	1.57	5.67	1.07693	99.71
5	48	15.983	12.547	650.7	171.15	40.73	0.01645	0.00670	5.89	2.31	5.73	5.90	2.31	5.66	1.04338	99.60
5	49	16.069	13.006	651.3	167.98	43.09	0.01549	0.00667	8.00	8.96	4.70	8.02	8.97	4.68	1.05880	98.77
5	50	19.517	15.519	913.4	233.16	47.36	0.01809	0.00857	1.06	0.03	19.44	0.64	0.02	24.93	1.10027	99.97
5	51	19.997	15.593	915.4	233.72	37.92	0.01781	0.00675	0.86	0.02	15.55	0.52	0.01	19.94	1.11695	99.98
5	52	19.884	15.627	915.7	227.61	27.97	0.01797	0.00503	1.36	0.03	12.71	0.82	0.02	16.33	1.09979	99.96
5	53	19.768	16.127	915.3	233.15	22.37	0.01800	0.00403	4.98	0.25	9.45	3.01	0.15	12.16	1.09588	99.85
5	54	19.891	16.042	916.7	229.02	20.17	0.01967	0.00397	4.81	0.15	10.90	2.90	0.09	14.06	1.12566	99.87
5	55	20.086	15.804	914.3	236.89	16.79	0.02211	0.00371	3.19	0.08	14.14	1.92	0.05	17.94	1.14454	99.92
5	60	19.719	16.107	940.8	232.54	16.46	0.02240	0.00369	2.64	0.06	16.87	1.40	0.03	23.09	1.12072	99.93
5	61	19.647	15.748	990.0	238.29	16.59	0.02255	0.00374	2.11	0.04	17.33	1.12	0.02	23.67	1.11059	99.95
5	411	16.094	12.433	651.2	164.12	40.33	0.01536	0.00619	4.87	4.92	3.79	4.88	4.92	3.86	1.13427	99.29
5	421	16.207	12.828	646.7	168.19	35.70	0.01621	0.00579	4.85	4.13	3.78	4.86	4.14	3.77	1.14624	99.41
5	421	18.114	14.129	652.8	168.97	39.34	0.01329	0.00523	5.13	4.93	3.75	5.14	4.94	3.77	1.29151	99.29
5	4212	16.012	12.331	651.1	164.62	39.39	0.01549	0.00610	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX C
DATA SUMMARY SHEET
(Run 6)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference			Engine Reference			Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
									CO EI	THC EI	NO_x EI	CO EI	THC EI	NO_x EI		
6	11	15.882	11.691	315.5	147.92	33.33	0.00001	0.00000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	12	18.086	13.406	313.7	147.63	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	12	18.184	13.512	316.3	147.78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	13	8.161	6.044	397.1	64.53	99.95	0.01369	0.01368	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	131	7.376	5.461	401.2	63.80	99.95	0.01518	0.01517	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	20	7.135	5.261	406.0	61.69	99.93	0.01213	0.01212	14.74	1.12	4.36	14.74	1.12	4.38	1.23396	99.52
6	21	7.144	5.280	406.2	59.96	99.92	0.01071	0.01071	16.54	1.60	4.31	16.54	1.60	4.36	1.22074	99.41
6	23	7.251	5.494	407.1	62.65	99.91	0.00941	0.00940	18.88	3.61	3.94	18.88	3.61	3.93	1.21476	99.14
6	24	7.329	5.589	407.8	62.16	99.91	0.00892	0.00891	21.83	5.79	3.69	21.83	5.79	3.69	1.21166	98.81
6	40	15.983	11.629	666.7	168.54	99.98	0.01509	0.01509	1.19	0.03	9.96	1.19	0.03	9.90	1.28648	99.97
6	41	16.020	11.665	630.8	166.95	50.49	0.01618	0.00817	4.88	1.96	7.97	4.89	1.96	7.92	1.22823	99.66
6	42	15.857	11.498	670.4	168.83	45.08	0.01638	0.00738	4.50	1.46	6.43	4.50	1.46	6.40	1.18699	99.72
6	43	16.034	11.826	673.5	168.61	42.44	0.01648	0.00699	4.04	1.69	5.43	4.05	1.69	5.40	1.22396	99.71
6	44	15.956	11.860	672.4	168.82	61.13	0.01621	0.00991	5.71	3.48	8.68	5.72	3.49	8.64	1.29352	99.46
6	441	15.993	11.913	667.3	105.48	60.99	0.01616	0.00986	5.63	3.36	8.70	5.64	3.37	8.64	1.30220	99.48
6	45	15.720	11.310	669.9	166.85	64.14	0.01643	0.01054	6.61	3.77	9.00	6.62	3.78	8.96	1.27840	99.41
6	46	16.227	12.089	666.3	168.37	41.45	0.01601	0.00664	4.08	1.32	5.51	4.08	1.32	5.46	1.27139	99.75
6	47	15.760	11.776	671.5	172.87	39.23	0.01686	0.00661	2.99	0.74	5.67	3.00	0.74	5.59	1.26920	99.85
6	48	16.062	11.634	667.9	166.53	43.42	0.01548	0.00672	4.36	3.18	5.43	4.36	3.19	5.41	1.26077	99.53
6	49	15.866	10.361	667.4	165.57	44.33	0.01539	0.00682	6.35	7.79	5.02	6.36	7.81	5.04	1.24201	98.93
6	49	16.142	11.884	674.4	163.49	42.44	0.01465	0.00622	8.46	14.81	3.44	8.47	14.84	3.46	1.26723	98.04
6	50	19.736	14.718	934.7	235.71	49.82	0.01775	0.00884	0.64	0.03	20.17	0.38	0.02	25.62	1.22731	99.98
6	51	19.943	15.910	935.0	239.74	41.74	0.01812	0.00756	0.45	0.02	18.08	0.27	0.01	22.84	1.26183	99.99
6	52	19.800	14.313	914.1	238.04	36.00	0.01823	0.00656	0.43	0.01	16.80	0.26	0.01	21.22	1.26774	99.99
6	53	20.228	14.728	937.2	241.48	25.00	0.01786	0.00447	1.20	0.07	12.87	0.73	0.04	16.26	1.27531	99.96
6	54	20.129	13.983	935.3	235.50	22.51	0.01990	0.00448	1.13	0.07	13.72	0.68	0.04	17.54	1.30990	99.97
6	55	19.637	14.473	930.9	244.15	19.86	0.02283	0.00453	0.94	0.05	16.59	0.57	0.03	20.78	1.28412	99.97

APPENDIX C
DATA SUMMARY SHEET
(Run 7)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
7	10	14.380	10.881	300.6	147.13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	10	14.280	10.848	299.6	146.97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	10	14.300	10.776	299.5	147.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	11	17.150	13.136	300.9	149.52	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	20	7.600	6.096	388.7	62.33	100.00	0.01158	0.01158	23.01	2.14	4.20	23.01	2.14	4.20	1.09864	99.21
7	11	17.090	13.197	299.9	149.97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	11	17.050	12.855	299.0	148.86	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	11	16.770	12.763	302.2	148.41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	12	18.800	14.591	301.2	150.44	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	12	18.800	14.558	303.8	151.44	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	12	18.800	14.680	298.8	150.14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	21	7.700	5.884	391.9	61.96	100.00	0.01000	0.01000	30.53	5.17	4.29	30.53	5.17	4.29	1.09499	98.67
7	22	7.700	5.982	391.3	62.02	100.00	0.00900	0.00900	36.02	10.08	4.11	36.02	10.08	4.12	1.10349	97.95
7	23	7.680	5.876	375.2	62.27	100.00	0.01072	0.01072	28.33	3.90	4.50	28.33	3.90	4.50	1.08322	98.88
7	41	15.590	11.821	654.8	163.36	54.55	0.01487	0.00811	18.22	29.52	6.95	18.26	29.57	7.01	1.06309	96.05
7	42	15.498	11.431	659.7	163.84	49.42	0.01515	0.00749	17.08	40.82	5.64	17.11	40.89	5.71	1.04267	94.70
7	43	16.010	11.985	656.8	163.19	52.56	0.01453	0.00764	17.73	33.05	6.47	17.76	33.11	6.52	1.07442	95.65
7	44	15.700	11.970	661.8	168.51	48.04	0.01598	0.00768	13.95	18.69	6.18	13.98	18.73	6.18	1.05333	97.48
7	45	15.700	11.922	654.8	164.84	56.77	0.01590	0.00903	14.26	13.81	8.22	14.29	13.84	8.23	1.05540	98.04
7	46	15.700	12.407	658.7	166.40	66.64	0.01580	0.01053	13.09	8.54	11.76	13.12	8.55	11.75	1.06239	98.69
7	47	15.580	11.803	656.7	168.03	79.45	0.01588	0.01262	9.28	4.63	9.82	9.30	4.64	9.81	1.07382	99.24
7	48	15.900	12.198	661.4	169.87	87.69	0.01542	0.01352	6.00	2.12	9.88	6.01	2.12	9.85	1.10016	99.61
7	48	15.800	11.681	658.5	166.06	100.00	0.01464	0.01464	3.15	0.76	9.86	3.16	0.76	9.89	1.17901	99.84
7	49	16.010	11.710	661.8	166.31	85.33	0.01425	0.01216	8.41	3.68	10.49	8.42	3.69	10.56	1.08963	99.36
7	50	15.800	11.714	657.3	167.01	79.83	0.01446	0.01154	6.65	5.26	20.94	5.22	3.18	31.77	1.08058	98.86
7	50	19.900	15.195	924.9	229.74	48.62	0.01822	0.00886	1.28	0.11	19.70	0.77	0.07	25.43	1.01978	99.96
7	51	19.640	15.132	925.0	228.93	45.31	0.01839	0.00833	1.50	0.10	18.70	0.90	0.06	24.16	0.99380	99.95
7	52	19.650	15.112	922.8	237.54	36.70	0.01853	0.00680	1.87	0.09	14.96	1.13	0.06	18.93	0.98132	99.95
7	54	19.900	15.304	924.6	239.69	27.45	0.01824	0.00501	2.36	0.09	11.39	1.43	0.06	14.38	1.00234	99.94

APPENDIX C
DATA SUMMARY SHEET
(Run 8A)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
8A	20	7.797	6.224	386.7	62.97	100.00	0.01160	0.01160	12.54	0.91	5.49	12.54	0.91	5.48	1.09892	99.60
8A	21	7.772	6.088	388.8	62.72	100.00	0.00955	0.00955	16.51	3.74	4.44	16.51	3.74	4.43	1.09330	99.18
8A	22	7.784	6.192	388.2	62.68	100.00	0.00867	0.00867	21.52	8.05	3.05	21.52	8.05	3.05	1.08449	98.55
8A	23	7.704	6.192	391.5	62.31	100.00	0.01055	0.01055	13.33	1.81	5.14	13.33	1.81	5.12	1.09395	99.48
8A	40	15.968	12.518	651.9	166.51	100.00	0.01404	0.01404	1.03	0.03	15.38	1.03	0.03	15.39	1.12038	99.97
8A	41	16.114	12.435	651.5	163.46	48.28	0.01400	0.00676	17.40	19.61	4.84	17.43	19.64	4.86	1.14460	97.27
8A	42	15.978	12.740	652.4	165.35	39.42	0.01412	0.00557	18.84	36.68	3.25	18.88	36.75	3.26	1.11715	95.23
8A	43	16.137	12.711	649.2	168.66	59.02	0.01401	0.00827	17.95	13.07	7.69	17.99	13.09	7.68	1.13797	98.05
8A	44	16.197	12.840	651.9	167.40	71.79	0.01398	0.01003	16.97	6.96	11.76	17.00	6.97	11.70	1.13034	98.80
8A	45	16.179	12.675	650.1	169.55	84.59	0.01394	0.01179	14.71	5.88	14.94	14.73	5.89	14.91	1.11113	98.97
8A	46	16.302	13.179	652.9	167.21	100.00	0.01374	0.01374	6.28	0.97	15.79	6.30	0.97	15.73	1.14938	99.74
8A	50	20.076	15.771	916.5	235.58	42.46	0.01675	0.00711	2.16	0.02	15.13	1.30	0.01	19.38	1.11216	99.95
8A	51	19.879	15.568	922.7	233.19	31.36	0.01691	0.00530	1.89	0.02	11.51	1.14	0.01	14.77	1.10987	99.95
8A	52	19.979	16.376	922.6	234.02	22.08	0.01677	0.00370	2.71	0.02	10.45	1.64	0.01	13.40	1.10696	99.93
8A	53	19.950	15.599	919.8	230.57	17.79	0.01879	0.00334	1.23	0.01	11.58	0.74	0.01	14.83	1.12357	99.97
8A	54	19.643	15.204	921.3	233.42	15.28	0.02212	0.00338	0.72	0.01	12.84	0.43	0.01	16.43	1.08750	99.98
8A	55	20.042	15.414	922.2	231.66	14.46	0.02250	0.00325	0.70	0.0	13.39	0.42	0.0	17.16	1.09841	99.98

APPENDIX C
DATA SUMMARY SHEET
(Run 8B)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
8B	20	7.910	6.422	386.7	62.35	100.00	0.01063	0.01063	24.62	9.27	3.85	24.62	9.27	3.83	1.10180	98.35
8B	20	7.886	6.198	386.7	62.76	100.00	0.01117	0.01117	19.12	4.52	4.29	19.12	4.52	4.27	1.09742	99.03
8B	21	7.800	6.139	383.7	63.61	100.00	0.01219	0.01219	14.42	1.67	5.17	14.42	1.67	5.12	1.08403	99.47
8B	23	7.569	6.056	387.2	63.09	100.00	0.01026	0.01026	31.24	18.86	3.69	31.24	18.86	3.67	1.07681	97.09
8B	40	15.960	13.272	648.2	166.54	100.00	0.01511	0.01511	1.09	0.02	12.39	1.10	0.02	12.41	1.12164	99.97
8B	40	15.953	12.255	660.6	166.25	100.00	0.01438	0.01438	1.23	0.01	12.62	1.24	0.01	12.70	1.10484	99.97
8B	41	15.700	12.626	661.8	164.36	49.50	0.01476	0.00730	12.40	32.50	2.68	12.42	32.56	2.69	1.06548	95.88
8B	42	16.018	12.713	654.2	164.41	60.74	0.01421	0.00863	10.11	11.74	6.72	10.12	11.76	6.77	1.11077	98.36
8B	43	16.172	12.865	651.7	167.38	82.41	0.01419	0.01169	8.31	4.71	11.85	8.33	4.72	11.93	1.13210	99.24
8B	44	15.794	12.522	655.0	167.68	100.00	0.01467	0.01467	3.91	1.24	12.93	3.91	1.24	12.94	1.10480	99.76
8B	45	15.823	12.161	663.7	163.99	86.73	0.01444	0.01252	7.34	4.51	12.19	7.35	4.52	12.28	1.10154	99.29
8B	46	15.940	12.499	660.2	168.48	77.54	0.01583	0.01227	7.82	4.40	11.58	7.83	4.40	11.52	1.10872	99.31
8B	47	16.137	12.694	656.6	175.17	69.20	0.01725	0.01194	7.29	3.01	10.76	7.30	3.02	10.61	1.12979	99.49
8B	50	19.931	15.726	918.8	230.26	44.84	0.01660	0.00744	3.30	0.04	14.59	1.99	0.02	18.86	1.06966	99.92
8B	51	20.340	15.915	919.6	231.98	33.25	0.01642	0.00546	6.26	0.23	9.52	3.78	0.14	12.28	1.10140	99.92
8B	52	19.906	15.593	896.4	234.93	39.22	0.01826	0.00716	1.10	0.02	15.68	0.66	0.01	20.01	1.07031	99.97
8B	53	19.801	15.369	927.1	235.96	35.11	0.02004	0.00704	0.61	0.0	15.31	0.37	0.0	19.53	1.03121	99.98

APPENDIX C
DATA SUMMARY SHEET
(Run 8C)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
8C	20	7.731	6.123	393.0	63.56	100.00	0.01033	0.01033	18.85	5.25	4.50	18.85	5.25	4.48	1.17706	98.95
8C	21	7.695	6.224	388.9	63.57	100.00	0.00927	0.00927	33.08	19.51	3.81	33.08	19.51	3.77	1.16977	97.00
8C	22	7.683	6.242	391.4	63.71	100.00	0.01198	0.01198	13.56	1.81	4.93	13.56	1.81	4.88	1.12212	99.48
8C	23	7.765	6.120	375.2	64.21	100.00	0.01263	0.01263	11.88	1.07	5.45	11.88	1.07	5.37	1.13320	99.61
8C	40	15.659	11.418	654.0	167.97	100.00	0.01518	0.01518	1.25	0.07	15.45	1.25	0.07	15.31	1.07019	99.96
8C	41	15.889	12.260	654.8	170.62	51.85	0.01540	0.00799	10.48	9.42	7.49	10.50	9.43	7.45	1.07082	98.67
8C	42	15.612	11.906	652.1	170.14	47.11	0.01518	0.00715	12.48	18.60	4.90	12.51	18.63	4.84	1.05899	97.59
8C	43	15.601	12.494	652.8	170.55	63.04	0.01562	0.00985	9.95	5.25	10.61	9.97	5.26	10.53	1.07600	99.16
8C	44	15.845	12.303	654.8	170.37	73.49	0.01522	0.01118	7.92	3.91	12.65	7.93	3.92	12.56	1.09024	99.36
8C	45	15.730	12.108	656.3	171.01	80.51	0.01544	0.01243	8.13	2.67	13.13	8.14	2.67	13.05	1.10088	99.50
8C	10	15.792	12.479	655.9	135.89	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	15.779	12.579	655.5	135.21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	15.783	12.526	659.9	136.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	15.862	12.515	652.9	136.91	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	15.803	12.461	659.3	136.87	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	15.951	12.750	657.9	136.85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	16.088	12.781	660.2	137.80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	16.053	12.741	656.3	136.69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	15.941	12.673	657.3	136.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	16.288	12.964	655.9	137.98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	15.804	12.525	659.3	136.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	15.681	12.388	661.2	137.12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8C	10	15.984	12.788	659.5	137.46	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX C
DATA SUMMARY SHEET
(Run 9A)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
9A	11	17.073	13.651	298.2	147.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	11	16.976	13.673	295.0	146.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	11	16.875	13.646	298.1	146.95	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	11	17.075	13.739	294.6	146.72	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	11	16.819	13.742	293.5	147.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	11	17.052	13.730	299.4	145.79	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	11	17.008	13.702	292.7	146.41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	11	16.996	13.798	294.5	147.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	11	17.036	13.738	297.4	146.88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	11	17.318	13.900	298.5	146.53	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	80	7.646	6.181	382.8	60.50	100.00	0.00873	0.00873	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9A	20	7.592	6.105	387.9	61.35	100.00	0.01128	0.01128	11.28	0.57	5.39	11.28	0.57	5.45	1.05127	99.66
9A	21	7.584	6.074	386.3	61.61	99.98	0.00963	0.00963	12.14	1.12	4.78	12.14	1.12	4.82	1.06698	99.58
9A	22	7.601	6.089	392.6	60.73	100.00	0.00835	0.00885	14.95	1.77	4.38	14.95	1.77	4.43	1.07642	99.43
9A	23	7.720	6.160	391.2	61.63	100.00	0.00789	0.00789	21.26	4.63	3.73	21.26	4.63	3.76	1.09569	98.94
9A	40	16.389	12.984	657.8	168.30	100.00	0.01445	0.01445	1.17	0.05	13.82	1.17	0.05	13.81	1.04216	99.97
9A	41	15.774	12.727	654.3	167.45	49.49	0.01525	0.00755	11.88	10.96	6.48	11.90	10.98	6.50	1.03892	98.43
9A	42	16.110	12.810	660.7	164.42	41.03	0.01491	0.00612	13.30	17.16	4.75	13.33	17.19	4.76	1.04918	97.66
9A	43	16.125	12.964	657.2	167.33	63.52	0.01470	0.00934	13.77	7.59	10.61	13.79	7.60	10.59	1.06210	98.79
9A	44	16.015	12.941	661.1	168.77	76.63	0.01496	0.01146	11.72	3.81	13.49	11.74	3.81	13.49	1.04904	99.28
9A	45	16.004	12.608	658.3	167.84	93.47	0.01521	0.01422	4.02	0.76	14.33	4.03	0.76	14.24	1.08880	99.82
9A	46	16.107	12.880	659.6	168.28	93.34	0.01411	0.01317	4.94	1.23	14.39	4.95	1.24	14.42	1.10417	99.74
9A	461	16.086	12.970	657.8	168.06	93.60	0.01410	0.01320	5.10	1.24	14.49	5.11	1.24	14.49	1.08458	99.73
9A	50	19.959	16.430	925.7	220.67	49.32	0.01813	0.00894	0.55	0.02	22.25	0.33	0.01	29.27	1.06822	99.98
9A	52	19.966	16.165	928.1	222.69	26.15	0.01795	0.00469	1.14	0.01	12.44	0.69	0.01	16.38	1.07149	99.97
9A	51	19.945	15.860	925.7	220.08	37.15	0.01803	0.00670	0.67	0.01	15.65	0.40	0.01	20.64	1.07559	99.98
9A	53	20.021	16.148	927.5	219.81	18.31	0.01786	0.00327	4.61	0.11	11.15	2.79	0.07	14.73	1.07750	99.87
9A	55	19.706	15.680	933.4	220.19	20.79	0.01822	0.00379	3.82	0.08	11.19	2.31	0.05	14.72	1.06725	99.90
9A	56	20.174	16.385	925.5	228.43	18.38	0.01974	0.00363	2.61	0.06	13.08	1.58	0.04	16.99	1.07821	99.93
9A	58	19.678	15.815	926.3	233.24	16.98	0.02241	0.00380	0.59	0.02	13.27	0.35	0.01	16.98	1.14314	99.98
9A	59	19.498	16.018	928.1	233.62	15.76	0.02339	0.00369	1.44	0.03	13.19	0.87	0.02	16.91	1.13826	99.96
9A	591	20.074	16.099	929.0	232.85	12.40	0.02267	0.00281	3.41	0.07	12.28	2.06	0.04	15.72	1.17543	99.91
9A	60	19.394	15.689	982.2	233.85	13.50	0.02093	0.00283	4.42	0.07	14.50	2.35	0.04	19.95	1.04441	99.89
9A	61	19.532	16.068	979.7	235.04	12.79	0.02243	0.00287	2.98	0.04	16.00	1.58	0.02	21.87	1.06049	99.93

APPENDIX C
DATA SUMMARY SHEET
(Run 10A)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
10A	11	17.084	13.645	305.2	149.41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	11	16.972	13.551	308.2	149.35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	11	17.032	13.606	302.7	148.87	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	11	17.125	13.716	305.8	148.92	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	11	17.200	13.764	308.1	149.57	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	11	17.097	13.774	301.0	150.18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	11	16.983	13.613	305.3	149.51	100.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	11	17.162	13.819	306.3	149.28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	11	17.142	13.773	301.6	149.14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	11	17.200	13.813	302.8	149.24	100.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10A	21	7.731	6.283	388.7	60.95	100.00	0.00974	0.00974	7.76	0.79	3.66	7.76	0.79	3.71	1.07992	99.72
10A	22	7.743	6.306	392.0	59.70	100.00	0.00891	0.00891	8.25	1.14	4.54	8.25	1.14	4.64	1.09724	99.66
10A	23	7.641	6.232	394.0	58.49	100.00	0.00834	0.00834	9.46	2.27	3.81	9.46	2.27	3.91	1.09700	99.49
10A	24	7.603	6.146	389.1	57.78	100.00	0.00729	0.00729	18.97	18.02	2.78	18.97	18.02	2.92	1.06505	97.18
10A	210	7.532	6.470	393.7	62.84	69.99	0.01547	0.01082	73.31	86.77	3.49	73.31	86.77	3.47	1.01571	88.27
10A	400	16.382	12.522	658.2	174.96	51.16	0.01512	0.00773	22.08	18.04	6.70	22.12	18.07	6.55	1.06643	97.48
10A	410	16.369	13.240	656.3	174.09	73.19	0.01459	0.01068	20.35	10.38	11.96	20.39	10.40	11.72	1.07754	98.37
10A	420	16.418	12.682	652.8	175.28	81.41	0.01443	0.01175	17.14	6.59	12.51	17.17	6.60	12.23	1.08915	98.88
10A	430	16.507	13.084	657.4	170.59	88.97	0.01444	0.01285	12.51	3.65	12.44	12.53	3.66	12.27	1.10316	99.30
10A	50	20.512	16.360	922.6	235.18	45.95	0.01841	0.00846	1.46	0.01	22.81	0.88	0.01	29.13	1.12123	99.96
10A	51	20.512	16.859	927.1	235.04	31.21	0.01841	0.00575	1.45	0.01	14.20	0.88	0.01	18.20	1.12123	99.96
10A	52	20.233	16.361	928.2	235.10	22.60	0.01853	0.00419	1.66	0.01	11.99	1.01	0.01	15.40	1.11698	99.96
10A	54	20.467	16.447	932.0	237.55	20.88	0.01995	0.00417	0.86	0.0	13.39	0.52	0.0	17.15	1.12695	99.98
10A	54	20.705	16.221	932.6	234.93	18.43	0.02161	0.00398	0.57	0.01	13.83	0.35	0.01	17.74	1.12453	99.98
10A	55	20.554	16.278	910.2	230.37	13.28	0.02154	0.00286	2.37	0.03	13.22	1.43	0.02	16.96	1.13789	99.94
10A	60	20.607	16.675	978.1	241.62	13.46	0.02154	0.00290	1.63	0.02	14.81	0.86	0.01	20.08	1.14861	99.96
10A	61	20.246	15.759	979.6	236.72	12.61	0.02285	0.00288	1.20	0.02	15.38	0.64	0.01	20.97	1.12583	99.97

APPENDIX C
DATA SUMMARY SHEET
(Run 10B)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
10B	20	7.673	6.197	393.5	64.74	100.00	0.01129	0.01129	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10B	20	7.613	6.214	390.2	63.29	100.00	0.01089	0.01089	10.76	0.18	5.26	10.76	0.18	5.21	1.05521	99.73
10B	21	7.630	6.186	393.8	62.88	100.00	0.00981	0.00981	8.92	0.24	4.65	8.92	0.24	4.63	1.04419	99.76
10B	22	7.665	6.203	389.4	62.04	100.00	0.00891	0.00891	12.20	1.73	3.85	12.20	1.73	3.86	1.03647	99.51
10B	23	7.719	6.264	392.9	61.07	100.00	0.00785	0.00785	37.82	20.95	2.61	37.82	20.95	2.64	1.04245	96.57
10B	40	16.271	13.019	658.8	169.13	86.41	0.01500	0.01296	6.95	3.86	12.52	6.97	3.87	12.49	1.07834	99.39
10B	41	16.251	12.776	656.1	164.92	80.09	0.01460	0.01169	8.38	6.42	13.06	8.39	6.43	13.11	1.08103	99.04
10B	42	16.468	13.995	656.3	166.30	72.51	0.01451	0.01052	12.31	10.02	13.16	12.33	10.04	13.15	1.05973	98.54
10B	50	20.007	15.889	911.5	234.21	44.52	0.01874	0.00834	2.30	0.09	19.48	1.39	0.05	25.05	1.05911	99.94
10B	51	19.783	16.169	914.1	230.60	30.22	0.01887	0.00570	2.27	0.06	12.15	1.37	0.04	15.59	1.02964	99.94
10B	52	19.802	15.762	919.5	234.48	21.45	0.01871	0.00401	2.56	0.06	10.73	1.54	0.04	13.69	1.03282	99.93
10B	53	19.909	15.834	921.4	233.13	20.12	0.02032	0.00409	1.39	0.02	12.36	0.84	0.01	15.70	1.02612	99.97
10B	54	20.207	16.403	919.3	243.68	17.93	0.02196	0.00394	0.56	0.01	11.19	0.34	0.01	14.05	1.06006	99.99

APPENDIX C
DATA SUMMARY SHEET
(Run 11)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
11	10	14.297	11.226	235.0	141.85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
11	11	15.190	11.956	243.6	149.73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
11	11	15.185	12.056	266.7	149.98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
11	11	7.306	5.825	352.8	61.67	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
11	11	7.383	5.885	347.3	61.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
11	80	7.700	6.158	380.8	62.02	100.00	0.00867	0.00867	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
11	20	7.585	6.050	385.1	62.35	100.00	0.01110	0.01110	10.73	0.11	4.95	10.73	0.11	4.94	0.99500	99.73
11	21	7.741	6.237	387.7	62.41	100.00	0.00956	0.00956	6.54	0.21	4.23	6.54	0.21	4.23	1.02014	99.82
11	23	7.644	6.028	385.1	62.00	100.00	0.00838	0.00838	15.76	4.06	3.10	15.76	4.06	3.11	0.98979	99.14
11	23	7.706	6.138	385.1	62.02	100.00	0.00832	0.00832	16.15	4.63	3.02	16.15	4.63	3.03	0.99696	99.07
11	40	15.873	12.365	653.7	169.71	100.00	0.01547	0.01547	1.87	0.03	12.86	1.87	0.03	12.77	0.99318	99.95
11	41	15.906	12.695	645.9	168.59	88.83	0.01537	0.01365	12.01	6.72	13.41	12.03	6.73	13.33	0.99992	98.94
11	42	16.305	12.605	650.4	170.46	88.46	0.01613	0.01427	10.98	4.72	12.59	11.00	4.73	12.44	1.00414	99.21
11	43	15.886	12.565	651.1	168.23	87.43	0.01423	0.01244	12.38	8.98	14.39	12.40	8.99	14.26	0.98762	98.68
11	44	16.001	12.605	655.1	168.26	88.32	0.01524	0.01346	9.70	5.87	13.73	9.72	5.88	13.63	1.00237	99.10
11	46	16.306	13.305	652.0	167.59	92.11	0.01426	0.01313	8.30	5.86	13.69	8.32	5.87	13.66	1.05208	99.12
11	50	19.734	15.691	925.9	233.95	44.59	0.01908	0.00851	0.86	0.04	20.50	0.52	0.02	26.13	0.99113	99.98
11	51	20.135	16.015	925.6	235.37	29.77	0.01887	0.00562	1.16	0.02	13.40	0.70	0.01	17.12	1.02546	99.97
11	52	20.192	15.655	923.8	233.29	21.29	0.01889	0.00402	1.88	0.02	12.51	1.13	0.01	15.98	1.03600	99.95
11	53	20.387	16.102	925.7	233.24	18.12	0.01866	0.00338	2.62	0.03	12.33	1.58	0.02	15.74	1.05062	99.94
11	54	19.947	15.949	926.1	233.92	20.00	0.02068	0.00414	1.19	0.01	13.17	0.72	0.01	16.78	1.01655	99.97
11	55	19.734	16.625	925.3	232.85	20.31	0.01996	0.00405	1.41	0.01	12.86	0.85	0.01	16.40	1.02534	99.97
11	57	19.768	15.660	927.2	232.92	27.89	0.02096	0.00585	0.68	0.01	15.44	0.41	0.01	19.60	0.97240	99.98

APPENDIX C
DATA SUMMARY SHEET
(Run 14)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
14	10	14.615	11.671	274.6	151.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	10	14.273	11.404	263.5	151.60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	10	14.392	11.445	296.0	151.54	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	10	14.482	11.509	305.0	151.88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	10	14.365	11.527	271.0	152.14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	10	14.603	11.442	278.1	150.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	10	14.363	11.427	281.9	151.94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	10	14.458	11.318	275.9	152.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	10	14.396	11.434	274.9	151.67	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	10	14.299	11.299	278.5	151.16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
14	20	7.586	6.077	393.1	63.96	100.00	0.01123	0.01123	10.74	0.16	5.47	10.74	0.16	5.40	1.03876	99.73
14	21	7.564	6.042	365.2	61.56	100.00	0.00908	0.00908	8.45	0.19	5.03	8.45	0.19	5.03	1.09017	99.78
14	21	7.731	6.184	391.4	62.23	100.00	0.00926	0.00926	8.34	0.19	4.84	8.34	0.19	4.84	1.05502	99.78
14	22	7.698	6.103	390.6	63.27	100.00	0.00818	0.00818	10.26	0.92	3.75	10.26	0.92	3.73	1.06375	99.65
14	23	7.656	6.189	363.2	62.37	100.00	0.00790	0.00790	14.44	1.72	3.80	14.44	1.72	3.79	1.05000	99.46
14	40	15.577	12.187	662.2	170.24	100.00	0.01490	0.01490	1.53	0.08	11.80	1.53	0.08	11.64	1.01701	99.96
14	41	16.101	12.603	666.0	171.00	48.19	0.01458	0.00703	20.04	13.48	7.06	20.07	13.50	6.98	1.02814	98.00
14	42	15.918	12.756	666.0	171.07	88.33	0.01456	0.01286	13.48	7.15	12.30	13.51	7.16	12.14	1.05169	98.88
14	43	15.844	12.587	663.9	169.43	78.95	0.01473	0.01163	14.39	8.37	13.05	14.42	8.38	12.95	1.02687	98.70
14	44	15.700	12.362	662.5	171.78	94.24	0.01495	0.01409	11.11	4.98	12.10	11.13	4.99	11.94	1.02617	99.18
14	50	19.717	15.774	914.7	231.55	19.93	0.01875	0.00374	1.74	0.04	12.34	1.05	0.02	15.68	1.05250	99.96
14	50	19.675	15.654	907.9	234.33	42.71	0.01846	0.00788	1.00	0.07	20.61	0.60	0.04	26.29	1.03301	99.97
14	51	19.749	16.048	914.7	234.25	27.12	0.01835	0.00498	1.47	0.0	13.39	0.89	0.0	17.08	1.03487	99.97
14	53	20.022	15.999	913.0	236.87	17.39	0.01974	0.00343	1.32	0.0	13.31	0.80	0.0	16.81	1.04637	99.97
14	54	20.177	16.140	914.0	240.20	15.88	0.02074	0.00329	1.09	0.04	13.84	0.66	0.03	17.45	1.06472	99.97

APPENDIX C
DATA SUMMARY SHEET
(Run 15)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
15	10	14.510	10.855	296.6	148.39	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94.72
15	10	14.660	10.991	294.2	147.69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.55
15	10	14.570	10.944	299.1	148.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.62
15	10	14.480	10.809	298.5	149.16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.31
15	10	14.450	10.918	296.2	148.64	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94.24
15	10	14.550	10.757	300.5	148.41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.97
15	10	14.530	11.023	299.0	147.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	96.02
15	10	14.380	10.853	298.6	148.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.80
15	10	14.490	10.904	300.5	148.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	92.04
15	10	14.570	10.877	299.2	148.47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
15	10	14.350	10.707	300.4	148.63	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.00
15	10	14.340	10.804	299.5	148.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.41
15	10	14.770	11.073	300.4	148.48	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	96.25
15	10	14.140	10.658	301.7	148.36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	96.80
15	80	7.650	5.728	380.1	61.49	100.00	0.00976	0.00976	1.32	29.51	0.0	1.57	35.14	0.0	0.00810	95.77
15	80	7.810	5.888	385.9	62.32	100.00	0.00900	0.00900	31.21	1.77	0.0	37.16	2.10	0.0	2.41310	98.88
15	80	7.850	5.940	384.6	56.82	100.00	0.00414	0.00414	0.0	6.41	0.0	0.0	7.64	0.0	0.05830	99.03
15	20	7.680	5.636	385.6	64.32	100.00	0.01100	0.01100	6.98	0.31	0.0	6.98	0.31	0.0	1.04330	99.80
15	21	7.700	5.795	386.8	63.75	100.00	0.00990	0.00990	5.80	0.20	0.0	5.80	0.20	0.0	1.04555	99.84
15	22	7.790	5.884	387.8	64.27	100.00	0.00880	0.00880	8.38	1.02	0.0	8.38	1.02	0.0	1.05720	99.69
15	23	7.570	5.712	387.8	62.79	100.00	0.00810	0.00810	29.52	13.13	0.0	29.52	13.13	0.0	1.01310	97.81
15	24	7.700	5.820	385.6	64.52	100.00	0.00840	0.00840	16.91	4.82	0.0	16.91	4.82	0.0	1.02940	99.06
15	40	15.810	11.794	638.8	169.88	100.00	0.01517	0.01517	0.90	0.0	0.0	0.91	0.0	0.0	1.03879	99.98
15	41	15.780	11.790	640.9	167.40	84.21	0.01590	0.01339	15.32	7.46	0.0	15.35	7.47	0.0	0.96860	98.78
15	41	15.920	12.260	642.1	168.04	84.21	0.01580	0.01331	15.10	8.96	0.0	15.13	8.97	0.0	0.98120	98.61
15	41	15.560	11.856	640.8	166.68	84.21	0.01529	0.01287	15.85	7.22	0.0	15.88	7.24	0.0	1.02675	98.79
15	42	15.700	12.042	642.4	166.86	85.00	0.01608	0.01367	15.04	5.11	0.0	15.07	5.12	0.0	1.04163	99.05
15	43	15.680	12.023	644.0	164.68	83.33	0.01440	0.01200	20.67	12.42	0.0	20.70	12.44	0.0	1.05660	98.05
15	431	15.750	12.073	643.5	164.65	83.33	0.01440	0.01200	19.11	13.17	0.0	19.14	13.19	0.0	1.05990	97.99
15	44	15.970	12.209	641.6	166.69	88.89	0.01420	0.01262	14.08	7.73	0.0	14.11	7.75	0.0	1.07450	98.75
15	45	15.700	11.910	641.7	165.75	80.00	0.01560	0.01248	18.27	10.62	0.0	18.30	10.64	0.0	1.04810	98.32
15	46	15.770	11.815	643.6	168.61	76.19	0.01655	0.01261	19.15	7.92	0.0	19.19	7.94	0.0	1.05652	98.63
15	50	20.090	15.558	926.5	231.99	48.28	0.01780	0.00859	5.32	0.10	0.0	3.21	0.06	0.0	1.11940	99.86
15	51	19.560	15.050	928.9	229.41	43.33	0.01850	0.00802	5.00	0.10	0.0	3.02	0.06	0.0	1.07630	99.87
15	52	19.830	15.136	928.2	233.85	30.00	0.01820	0.00546	5.32	0.10	0.0	3.21	0.06	0.0	1.05830	99.86
15	53	20.170	15.675	902.9	229.65	20.69	0.01785	0.00369	6.71	0.30	0.0	4.05	0.18	0.0	1.04308	99.81
15	54	20.340	15.760	904.2	229.72	18.75	0.01910	0.00358	4.68	0.10	0.0	2.83	0.06	0.0	1.05730	99.88
15	55	19.770	15.215	907.0	231.24	17.65	0.02110	0.00372	2.79	0.10	0.0	1.68	0.06	0.0	1.02840	99.92
15	551	19.930	15.091	905.2	228.69	17.65	0.02080	0.00367	2.78	0.10	0.0	1.68	0.06	0.0	1.04200	99.92
15	60	19.790	15.158	979.6	233.34	30.00	0.01820	0.00546	3.39	0.0	0.0	1.80	0.0	0.0	1.02380	99.92
15	61	20.060	15.257	981.3	234.67	17.24	0.01785	0.00308	5.22	0.10	0.0	2.77	0.05	0.0	1.05529	99.87
15	62	20.130	15.456	979.1	232.05	15.62	0.01950	0.00305	3.40	0.10	0.0	1.81	0.05	0.0	1.05270	99.91
15	63	20.160	15.541	983.9	233.46	14.29	0.02164	0.00309	1.70	0.0	0.0	0.90	0.0	0.0	1.04098	99.96

APPENDIX C
DATA SUMMARY SHEET
(Run 16)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
16	10	7.830	6.658	347.1	67.18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.08
16	10	7.420	6.114	422.8	63.32	100.00	0.01180	0.01180	0.0	0.0	0.0	0.0	0.0	0.0	1.86620	0.95
16	20	7.410	6.020	397.4	62.83	100.00	0.01150	0.01150	9.59	0.20	5.60	9.59	0.20	5.57	1.00370	0.93
16	21	7.410	6.125	393.0	61.73	100.00	0.01000	0.01000	6.54	0.30	4.78	6.54	0.30	4.80	1.00620	0.89
16	22	7.490	6.132	401.1	62.57	100.00	0.00890	0.00890	8.09	1.82	3.85	8.09	1.82	3.83	0.99600	0.90
16	23	7.320	5.985	405.0	62.64	100.00	0.00820	0.00820	15.74	8.07	2.94	15.74	8.07	2.92	1.00280	0.91
16	210	7.350	6.226	404.0	61.67	100.00	0.00976	0.00976	6.74	0.40	4.86	6.74	0.40	4.88	1.03626	0.95
16	236	7.420	6.276	402.3	62.12	100.00	0.00777	0.00777	16.18	8.93	2.98	16.18	8.93	2.99	1.06551	0.88
16	30	6.690	5.418	380.6	57.66	100.00	0.01240	0.01240	11.82	0.20	5.51	11.62	0.19	5.60	1.04240	0.92
16	31	6.750	5.555	392.4	58.28	100.00	0.01150	0.01150	9.96	0.20	5.18	9.79	0.20	5.23	1.04300	0.87
16	32	6.750	5.445	390.5	58.26	100.00	0.01060	0.01060	8.19	0.20	4.95	8.05	0.19	5.03	1.04460	0.97
16	320	6.800	5.360	390.5	57.72	100.00	0.01090	0.01090	8.28	0.10	5.02	8.14	0.10	5.07	1.04190	0.97
16	310	15.800	12.701	619.0	163.66	100.00	0.01530	0.01530	3.37	0.0	5.43	3.31	0.0	3.26	1.02100	1.11
16	41	15.810	12.915	600.2	169.66	100.00	0.01520	0.01520	16.96	8.07	16.38	16.99	8.09	16.19	1.03230	0.99
16	42	16.010	13.108	632.1	172.91	100.00	0.01580	0.01580	15.87	4.92	15.00	15.90	4.92	14.81	1.04630	1.00
16	43	15.890	12.868	628.7	165.89	100.00	0.01420	0.01420	23.03	14.62	15.47	23.07	14.64	15.44	1.02610	0.98
16	44	16.100	13.119	634.2	168.33	100.00	0.01410	0.01410	16.46	8.53	15.96	16.49	8.55	15.91	1.04480	1.01
16	45	15.910	12.973	632.7	162.66	100.00	0.01640	0.01640	20.30	7.35	14.14	20.33	7.37	14.27	1.01640	0.92
16	46	15.790	12.813	567.5	162.77	100.00	0.01540	0.01540	28.71	16.13	16.13	28.76	16.15	16.25	1.00610	0.91
16	47	15.870	12.865	632.1	170.19	100.00	0.01790	0.01790	18.63	3.68	14.15	18.66	3.69	13.97	0.99170	0.95
16	48	16.050	13.027	637.5	168.35	100.00	0.01640	0.01640	19.30	5,05	14.85	19.34	5.06	14.76	1.00390	0.98
16	49	16.070	12.978	632.9	165.26	100.00	0.01560	0.01560	17.13	4.88	15.77	17.16	4.89	15.79	1.00600	1.01
16	50	20.180	17.017	882.8	231.81	47.12	0.01800	0.00848	5.84	0.0	19.59	3.53	0.0	25.11	1.01690	0.99
16	51	19.900	16.156	890.0	229.16	43.34	0.01810	0.00785	5.61	0.10	17.18	3.39	0.06	22.09	1.00620	0.93
16	52	20.310	16.497	869.3	231.45	30.03	0.01780	0.00535	5.80	0.20	12.79	3.51	0.12	16.45	1.02230	0.86
16	53	20.000	16.370	884.4	231.27	21.02	0.01810	0.00380	6.81	0.20	11.71	4.11	0.12	15.06	1.00210	0.84
16	54	20.490	16.629	888.4	228.95	19.24	0.01910	0.00368	4.01	0.10	12.82	2.42	0.06	16.47	1.04110	0.84
16	55	20.270	16.468	891.2	230.48	18.02	0.02080	0.00375	2.61	0.10	14.04	1.57	0.06	18.05	1.02210	0.83
16	56	20.210	16.462	914.5	231.61	17.37	0.02180	0.00379	1.81	0.0	14.15	1.09	0.0	18.14	1.02590	0.81
16	57	20.540	16.388	911.3	234.54	24.58	0.02140	0.00526	1.41	0.0	14.62	0.85	0.0	18.75	1.04050	0.75

APPENDIX C
DATA SUMMARY SHEET
(Run 18A)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
18A	131	12.170	-1.000	393.9	81.56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	132	10.950	-1.000	392.8	79.78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	132	11.220	-1.000	392.9	79.80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	133	11.340	-1.000	393.0	86.64	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	133	11.490	-1.000	393.5	86.94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	134	10.600	-1.000	392.4	73.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	134	10.420	-1.000	392.7	73.78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	112	41.240	-1.000	397.6	278.51	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.15
18A	130	41.370	-1.000	398.1	278.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	113	35.250	-1.000	399.7	274.14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	113	28.510	-1.000	404.0	228.33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18A	113	30.960	-1.000	401.7	244.17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.07
18A	113	34.650	-1.000	397.0	274.36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.05
18A	130	27.790	-1.000	402.0	309.89	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.06

APPENDIX C
DATA SUMMARY SHEET
(Run 18B)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
18B	10	8.430	-1.000	249.7	53.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
18B	10	8.320	-1.000	397.9	52.73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
18B	10	7.410	-1.000	409.2	58.38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
18B	10	7.430	-1.000	405.7	58.92	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
18B	120	15.030	-1.000	539.1	123.57	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
18B	120	15.300	-1.000	520.2	123.13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
18B	120	14.640	-1.000	498.7	123.44	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

APPENDIX C
DATA SUMMARY SHEET
(Run 19)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
19	10	22.370	-1.000	391.8	200.52	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	20.790	-1.000	384.1	199.16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	21.250	-1.000	384.0	199.18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	21.570	-1.000	388.5	198.43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	21.320	-1.000	392.0	198.71	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	21.290	-1.000	359.3	198.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	21.230	-1.000	359.3	198.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	22.020	-1.000	360.0	198.94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	21.680	-1.000	359.8	198.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	21.600	-1.000	361.4	197.55	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	21.730	-1.000	395.0	198.43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	22.370	-1.000	364.6	198.47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	10	22.110	-1.000	365.5	197.68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	21	7.690	-1.000	366.3	62.80	100.00	0.00870	0.00870	8.85	2.31	4.45	8.85	2.31	4.44	1.13260	
19	210	7.500	-1.000	367.9	62.87	100.00	0.00890	0.00890	7.37	2.22	4.34	7.37	2.22	4.32	1.10510	
19	22	7.350	-1.000	369.1	62.93	100.00	0.01140	0.01140	8.92	0.10	6.44	8.92	0.10	6.39	1.06270	
19	220	16.160	-1.000	608.2	171.46	100.00	0.01300	0.01300	3.02	0.0	6.06	3.02	0.0	3.65	1.03440	

APPENDIX C
DATA SUMMARY SHEET
(Run 20)

Run	Point	Airflow Total lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
20	10	22.540	-1.000	411.9	201.81	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
20	10	22.450	-1.000	411.8	202.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
20	10	22.800	-1.000	412.1	201.12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
20	10	22.310	-1.000	412.2	200.92	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
20	10	22.660	-1.000	412.7	201.22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
20	10	22.700	-1.000	413.0	201.80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
20	10	23.090	-1.000	413.7	201.62	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
20	20	7.650	-1.000	404.0	60.57	100.00	0.00890	0.00890	8.16	2.46	3.84	8.16	2.46	3.87	1.24880	
20	21	7.640	-1.000	393.9	61.46	100.00	0.00960	0.00960	7.44	0.89	4.70	7.44	0.89	4.72	1.22670	
20	22	7.710	-1.000	387.3	61.50	100.00	0.01060	0.01060	8.33	0.10	5.92	8.33	0.10	5.95	1.23380	
20	25	7.650	-1.000	386.3	62.67	100.00	0.01080	0.01080	18.07	4.76	4.94	18.07	4.76	4.96	0.60940	
20	221	7.520	-1.000	384.5	61.38	100.00	0.01100	0.01100	10.02	0.30	5.68	10.02	0.30	5.71	1.07650	
20	40	34.870	-1.000	979.9	438.69	18.06	0.02320	0.00419	0.0	-17.84	0.0	0.0	-17.87	0.0	-0.00510	
20	50	36.740	-1.000	949.6	441.80	0.0	0.02320	0.0	0.76	0.0	17.50	0.46	0.0	16.34	1.24450	
20	55	36.040	-1.000	949.5	441.51	16.98	0.02390	0.00406	0.76	0.0	17.40	0.46	0.0	16.23	1.21260	

APPENDIX C
DATA SUMMARY SHEET
(Run 21)

Run	Point	Airflow Total Lb/sec	Airflow Combustor lb/sec	Inlet Temp °F	Inlet Press Psia	% Pilot Fuel Flow	Fuel Air Combustor	Fuel Air Pilot	Rig Reference CO EI	Rig Reference THC EI	Rig Reference NO_x EI	Engine Reference CO EI	Engine Reference THC EI	Engine Reference NO_x EI	Fuel Air C.B. / Fuel Air Meas	Combustion Efficiency
21	0001		04/03/81	390.1	66.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
21	0002		04/03/81	391.6	65.71	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
21	0003		04/03/81	395.2	66.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
21	1102	JET A	04/03/81	394.7	61.68	100.00	0.0067	0.0067	0.0	17.33	2.38	0.0	16.97	2.19	0.021	98.04
21	1203	ERBS	04/03/81	399.2	63.90	100.00	0.0080	0.0080	3.28	5.84	0.0	3.33	5.92	0.0	0.028	99.23
21	1404	11.8%	04/03/81	401.3	62.55	100.00	0.0071	0.0071	10.40	2.95	9.51	10.33	2.93	8.59	0.198	99.40
21	1105	JET A	04/03/81	395.8	63.44	100.00	0.0081	0.0081	10.42	6.30	4.27	10.49	6.34	3.87	1.257	99.02
21	1106	JET A	04/03/81	397.3	64.85	100.00	0.0096	0.0096	9.12	1.90	6.06	9.39	1.96	5.42	1.212	99.56
21	1107	JET A	04/03/81	399.9	65.21	100.00	0.0120	0.0120	10.35	0.09	7.06	10.71	0.09	6.26	1.225	99.74
21	1208	ERBS	04/03/81	397.4	64.29	100.00	0.0086	0.0086	10.58	4.63	4.39	10.80	4.72	3.94	1.142	99.19
21	1209	ERBS	04/03/81	397.3	63.36	100.00	0.0097	0.0097	10.37	2.17	6.30	10.43	2.18	5.70	1.161	99.50
21	1210	ERBS	04/03/81	396.3	65.09	100.00	0.0118	0.0118	12.13	0.25	7.66	12.53	0.26	6.85	1.196	99.67
21	1411	11.8%	04/03/81	400.2	63.58	100.00	0.0084	0.0084	10.20	3.83	4.55	10.29	3.87	4.09	1.292	99.29
21	1412	11.8%	04/03/81	399.3	63.10	100.00	0.0098	0.0098	10.10	1.51	6.17	10.12	1.51	5.57	1.299	99.58
21	1413	11.8%	04/03/81	400.1	62.33	100.00	0.0118	0.0118	13.24	0.12	7.49	13.10	0.12	6.79	1.282	99.67
21	2114	JET A	04/03/81	660.7	168.02	86.80	0.0146	0.0127	8.58	2.40	15.68	8.58	2.40	14.35	1.231	99.52
21	2115	JET A	04/03/81	656.3	167.55	89.42	0.0140	0.0125	8.75	2.64	15.92	8.73	2.63	14.71	1.226	99.49
21	2116	JET A	04/03/81	655.8	170.47	80.95	0.0157	0.0127	14.34	4.07	15.40	14.55	4.13	14.12	1.179	99.19
21	2217	ERBS	04/03/81	662.7	167.61	85.13	0.0145	0.0123	17.22	4.66	17.10	17.18	4.65	15.60	1.237	99.05
21	3118	JET A	04/03/81	904.2	197.54	21.72	0.0201	0.0044	1.22	0.08	13.51	1.19	0.08	12.45	1.179	99.96
21	3219	ERBS	04/03/81	897.8	197.51	21.58	0.0206	0.0044	1.38	0.06	14.99	1.34	0.06	13.98	1.186	99.96
21	4120	JET A	04/03/81	941.5	298.70	30.11	0.0182	0.0055	1.73	0.06	14.82	1.35	0.05	15.21	1.128	99.96
21	4121	JET A	04/03/81	920.8	297.44	20.75	0.0180	0.0037	6.18	0.61	12.55	4.78	0.47	13.43	1.117	99.83
21	4122	JET A	04/03/81	922.9	296.86	14.89	0.0183	0.0027	15.01	3.03	12.15	11.60	2.34	12.96	1.128	99.46
21	4123	JET A	04/03/81	923.9	299.56	15.35	0.0247	0.0038	2.33	0.08	18.62	1.82	0.06	19.74	1.132	99.95
21	5124	JET A	04/03/81	935.3	368.96	20.77	0.0204	0.0042	1.40	0.05	18.63	1.34	0.05	17.41	1.113	99.96
21	5225	ERBS	04/03/81	935.3	368.27	19.75	0.0212	0.0042	1.29	0.04	22.13	1.24	0.04	20.70	1.186	99.97
21	5138	JET A	04/03/81	941.8	374.00	17.15	0.0224	0.0038	0.91	0.03	22.14	0.89	0.03	20.29	1.133	99.98
21	6126	JET A	04/06/81	1015.0	400.49	20.96	0.0184	0.0039	1.78	0.10	23.03	1.61	0.09	21.25	1.170	99.95
21	6127	JET A	04/06/81	1000.8	401.61	19.18	0.0213	0.0041	1.00	0.09	25.96	0.90	0.08	24.59	1.140	99.97
21	6128	JET A	04/06/81	1014.5	404.59	17.34	0.0222	0.0038	0.74	0.08	29.17	0.67	0.07	26.81	1.177	99.98
21	6130	JET A	04/06/81	1008.9	399.10	29.31	0.0206	0.0060	0.38	0.04	26.08	0.34	0.04	24.39	1.137	99.99
21	6131	JET A	04/06/81	1011.3	402.09	38.78	0.0197	0.0076	0.33	0.04	35.84	0.30	0.04	33.24	1.141	99.99
21	6232	ERBS	04/06/81	1017.9	402.04	20.68	0.0196	0.0041	0.58	0.04	26.86	0.53	0.04	24.60	1.177	99.98
21	6233	ERBS	04/06/81	1004.5	404.30	31.28	0.0195	0.0061	0.39	0.04	29.23	0.36	0.04	27.39	1.171	99.99
21	6234	ERBS	04/06/81	1020.8	402.26	39.42	0.0207	0.0082	0.39	0.04	36.66	0.35	0.04	33.38	1.064	99.99
21	6435	11.8%	04/06/81	1013.9	402.07	20.78	0.0207	0.0043	0.67	0.03	28.32	0.61	0.03	26.14	1.130	99.98
21	6436	11.8%	04/06/81	1012.2	401.50	30.19	0.0203	0.0061	0.41	0.03	30.79	0.37	0.03	28.53	1.149	99.99
21	6437	11.8%	04/06/81	1019.2	403.81	38.10	0.0187	0.0071	0.32	0.03	39.08	0.29	0.03	35.62	1.244	99.99

LIST OF ABBREVIATIONS AND SYMBOLS

AC_d	effective flow area
Ae	exit area
avg	average
CO	carbon monoxide
De	exit diameter
Di	inlet diameter
EGV	exit guide vane
EI	emissions index
EPAP	Environmental Protection Agency Parameter
F/A	fuel/air ratio
FPS	Flight Propulsion System
ID	inner diameter
ICLS	Integrated Core/Low Spool
L	length
$L/\Delta R$	length to radius ratio
LBO	lean blowout
msec	millisecond
NO_x	oxides of nitrogen
OD	outer diameter
PDR	Preliminary Design Review
P_{T3}	diffuser inlet total pressure
pj/p_∞	density ratio
$\Delta P/P$	pressure loss
R	radius
SAE	Society of Automotive Engineer
SLTO	sea level takeoff
SMD	Sauter mean diameter
T	temperature
ΔT	temperature rise
T_{T3}	diffuser inlet total temperature
T_{T4}	combustor exit total temperature
THC	total hydrocarbons
TOBI	tangential on-board injection
U	velocity
uj/u	vane length swirler
W_A	air flow
W_{A3}	diffuser inlet flow
W_B	combustor flow
X/D	axial position
y/D	radial penetration
β	angle
Δ	difference
ϕ	equivalence ratio
γ	angle

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